AD/A-004 614

# U. S. AND SOVIET MHD TECHNOLOGY: A COMPARATIVE OVERVIEW

G. Rudins

Rand Corporation
Santa Monica, California

January 1974

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

# REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

| | |
|---|---|
| 1. REPORT NUMBER<br>R-1404-ARPA | 2. GOVT ACCESSION NO. |
| 3. RECIPIENT'S CATALOG NUMBER<br>AD/A-004614 | |
| 4. TITLE (and Subtitle)<br>U.S. and Soviet MHD Technology: A Comparative Overview | 5. TYPE OF REPORT & PERIOD COVERED<br>Interim |
| | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s)<br>G. Rudins | 8. CONTRACT OR GRANT NUMBER(s)<br>DAHC15 73 C 0181 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>The Rand Corporation<br>1700 Main Street<br>Santa Monica, California 90406 | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>Defense Advanced Research Projects Agency<br>Department of Defense<br>Arlington, Virginia 22209 | 12. REPORT DATE<br>January 1974 |
| | 13. NUMBER OF PAGES<br>112 |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) | 15. SECURITY CLASS. (of this report)<br>UNCLASSIFIED |
| | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

No Restrictions

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

MAGNETOHYDRODYNAMICS
ENERGY
USSR--TECHNOLOGY

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

see reverse side



DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Based on comprehensive coverage of the open Soviet and international conference literature, reviews developments in magnetohydrodynamic power generation, in which the Soviet program far exceeds the American. The USSR now operates the first MHD power plant, currently attaining 5 MW(e) of a planned 25 MW(e) output, considered to be about 5 years ahead of the U.S. The U.S., because of early concentration on military applications, is more advanced in high performance closed-cycle MHD generators. Open-cycle MHD offers the possibility of very simply constructed low-pollution electric power plants of improved conversion efficiencies, using plentiful high-sulfur coal, for capital outlays comparable to conventional turbine plants. This report reviews MHD technology, the evolution of MHD programs, facilities and objectives, and discusses U.S./USSR cooperation (the record of the first meeting of the Standing Steering Committee is appended). A second report will cover MHD materials research, perhaps the major problem area. 111 pp. Ref. (MW)

The research described in this Report was sponsored by the Defense Advanced Research Projects Agency under contract No. DAHC15-73-C-0181. Reports of The Rand Corporation do not necessarily reflect the opinions or policies of the sponsors of Rand research.

ARPA ORDER NO.: 189-1
3F10 Nuclear Monitoring Research

R-1404-ARPA
January 1974

# U. S. and Soviet MHD Technology: A Comparative Overview

G. Rudins

A Report prepared for

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

Rand
SANTA MONICA, CA. 90406

ii a

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

## PREFACE

This Report is part of a continuing Rand study, sponsored by the Defense Advanced Research Projects Agency, of selected areas of Soviet science and technology. It is based on comprehensive coverage of the Soviet literature exclusively in the public domain, as well as on exchanges between U.S. and Soviet specialists at international MHD conferences and meetings.

The present Report is the first of two that will deal with Soviet magnetohydrodynamic (MHD) research and development; it provides an overview of U.S. and Soviet hardware developments, with special emphasis on open-cycle MHD, the area in which most of the Soviet MHD effort appears to be concentrated. The second report will examine in greater detail developments in U.S. and USSR MHD materials research, perhaps the major problem area in MHD technology.

## SUMMARY

The size and scope of the Soviet MHD-power generation program far exceeds that of the United States. The USSR is now operating the world's first MHD power plant, currently attaining 5 MW(e) of a 25-MW(e) planned power output. The Soviet closed-cycle MHD program appears to be small and lags that of the United States; the Soviet open-cycle effort (representing about 80 percent of their visible MHD research) leads that of the United States, which is believed to be about five years away from the construction of a pilot plant of the Soviet type. The USSR has considerable experience in integrated plant operation, while the United States, because of its early concentration on military applications, has a substantially advanced understanding of high-performance MHD-generator operation.

The commercial potential of open-cycle (and to a lesser extent, closed-cycle) MHD power generation is considerable, especially in view of current energy problems. Provided certain technological problems can be resolved, MHD offers the possibility of low-pollution electric-power plants of very simple construction (i.e., no moving parts) with considerably improved conversion efficiencies, using plentiful high-sulfur coal, at capital costs comparable to those of conventional turbine plants. A recently negotiated U.S.-Soviet agreement provides the possibility of coordinating the two approaches to the benefit of both countries.

The present Report, in successive sections, briefly reviews MHD technology, traces the evolution of the MHD programs in the United States and USSR and their respective development approaches, and compares major U.S. and USSR MHD facilities and national program objectives.

**Preceding page blank**

# CONTENTS



Preceding page blank

# I. INTRODUCTION

The relatively high degree of international cooperation in magnetohydrodynamics (MHD) has provided a particularly broad and detailed literature; for this reason, this Report is based exclusively on actual data in the open literature on the subject. Much of the information occurs in the proceedings of a series of international conferences sponsored by the OECD(NEA)/IAEA International MHD Liaison Group in which the Soviets have been active participants. The three reports prepared by the group in 1967 [1], 1969 [2], and 1972 [3], under British, American, and Soviet editorship, respectively, have proved especially useful. Although the USSR, like other countries involved in MHD development, has published a large number of reports, Soviet specialists tend to present their most up-to-date results and their most interesting engineering developments at international conferences. Soviet papers delivered at the Fifth International Conference on MHD Electrical Power Generation in Munich, April 19-23, 1971, and at the most recent meeting of the MHD Liaison Group in January 1973 were especially useful. Soviet publication in MHD tends to treat very narrow subject areas in great detail and, at the same time, to omit new hardware specifications; nevertheless, Soviet publications have also been extensively used in the preparation of this Report.

The present Report, in successive sections, briefly reviews MHD technology, power systems, and some of the applications for which MHD has been proposed or is currently being considered. However, since the Report's main purpose is to provide a comparative overview of U.S. and USSR technologies, a major part is devoted to the history of MHD development in these two countries, respective development approaches, and current status of individual programs.

The concluding section briefly reviews the information presented in detail in the main body of the Report. Finally, the outcome of current Soviet programs is estimated and the various implications for U.S. technology development are discussed.

## HISTORICAL BACKGROUND

Magnetohydrodynamic electrical power generation was first recognized by Michael Faraday as technically feasible during his original investigation of electromagnetic induction in 1831. It appears in the patent literature from the early 1900s. The first recorded attempt to develop an MHD generator was conducted at the Westinghouse Research Laboratories before and during World War II. After World War II, MHD emerged as one component of developing interests in the understanding and utilization of ionized gases or plasmas under high-temperature conditions. Several preliminary studies of the MHD-power-generation process were made in the United States in the late 1950s, and interest was expressed by both commercial electric-power systems organizations and the Department of Defense. The advent of the space program quickly established NASA interest.

Approximate calculations in the late fifties and early sixties indicated quick and early success; thus, a relatively ambitious large-scale program was undertaken in the United States, and two large open-cycle generators were built. Both of these efforts provided a valuable large-scale demonstration of MHD capability, but the performance was lower than that predicted by the relatively unsophisticated calculations then carried out. There followed a period in which MHD turned to small experiments in which the problems that plagued the large generators were adequately demonstrated and solutions found. The technically unfavorable climate generated by the early, relatively low performance was turned around when it became possible to demonstrate, in a fairly small apparatus, power densities and power-extraction rates that exceeded those in the larger, less sophisticated machines. Since the early 1960s, there have been substantial efforts in several countries in addition to the United States to develop this technology for a number of applications, and good progress has been made, although the first service application of MHD has yet to be undertaken.

After 1959, MHD programs developed rapidly. Of particular importance in the area of commercial MHD was the joint effort between the Avco Corporation and a group of private utilities headed by the American Electric Power Service Corporation. This group set out to develop MHD for coal-fired, baseload central-station application and made significant

progress in both MHD generator development and associated components. The work progressed far enough to include the preparation of preliminary engineering design of a 30-MW pilot plant, but in 1966, efforts by the Avco utility group to obtain government support for a joint pilot-plant venture failed, and shortly thereafter there was a very substantial curtailment of all MHD activities.

Soviet scientists have described the origin of Soviet MHD interest as follows. By the early 1950s information on the original pre-World War II experiments at the Westinghouse Research Laboratories and the immediate post-World War II work by Professor Thring and his associates at the University of Sheffield in England had reached the USSR. That and the successful feasibility demonstrations in the United States in 1959 provided V. A. Kirillin, now Chairman of the Committee for Science and Technology, and A. E. Sheindlin with the rationale to initiate an MHD-research development program in 1961. Sheindlin's assumption of the directorship of the Institute of High Temperatures provided an opportunity to develop MHD within this organization, which up to then had been concerned with the systematic study of conventional high-temperature properties of materials.

Talk of a Soviet MHD program reached the West in 1961. The first contact with the Soviet group was made in 1962, when Sheindlin and E. P. Velikhov, Deputy Director of the Kurchatov Institute of Atomic Energy, appeared at the First International Conference on MHD in Newcastle-upon-Tyne, England. Their impact was immediate: Sheindlin announced that the USSR had embarked on a program to develop commercial MHD, and Velikhov presented some fundamental analysis of the instabilities which could be expected under certain conditions in MHD plasmas.

The current Soviet MHD effort appears to be concentrated on open-cycle MHD applications, which have the most promising future at the present time, but work is also being carried out on closed-cycle systems. Open-cycle work began in the early sixties and, initially, consisted of fundamental physical and MHD research; this constituted Phase 1 of the program described by Sheindlin. By the mid-1960s, the Soviets began to develop a small-scale model of a complete commercial MHD plant (Phase 2), and in 1965, they completed this model, the U-02 installation, which has

since been used continually as their main small-scale experimental plant. The U-02 was followed by the larger Kiev facility and the still larger ENIN-2 in 1970. The highlight of the Soviet open-cycle effort and the beginning of their Phase 3 occurred in March 1971 with the startup of the U-25, the first complete, large-scale (25-MW MHD-power) central-station pilot plant. If the U-25 is successful, the Soviets plan to build at least one commercial-scale, intermediate-load and/or baseload MHD electrical power station (Phase 4).

Sheindlin's Institute of High Temperatures has always been in the forefront of the Soviet MHD effort and has been conducting research on practically every aspect of MHD technology development -- from plasma physics, materials development, and diagnostic techniques to the construction of complete open-cycle pilot plants and work on closed-cycle plasma and liquid-metal MHD. While the group at this Institute has been the largest visible component of the Soviet MHD program, other interests have developed as well -- notably, at the Krzhizhanovskiy Power Institute in Moscow, where a considerable amount of MHD generator testing has been done. The interest in coupling MHD to nuclear reactors for both space and terrestrial applications led to major activity for some years at the Kurchatov Institute of Atomic Energy under the general direction of the late Academician Millionshchikov and the immediate direction of Velikhov. Some of this work still continues, but is now, according to Velikhov, directed toward the possible utilization of a fusion reactor as the heat source for MHD.

Velikhov's fusion-related MHD work probably does not represent a late change in direction or application. Personnel at the Oak Ridge National Laboratory indicated that Velikhov appeared early with the idea of MHD conversion of fusion energy, and it may be that this has been the focus of his research all along. The short-time MHD experiments conducted in his new laboratory near Moscow could be viewed as efforts to simulate MHD fusion-energy conversion. Also, the analysis techniques used by Velikhov and many of his colleagues show a strong background in fusion-type studies.

World development of MHD from 1960 has been on a relatively intense basis, although the budgets involved have usually never been more than a few percent of the amounts devoted to the development of, for example,

nuclear reactors. At this level of effort, MHD development has not attained high-priority status in overall energy technology, and it has been pursued in an atmosphere of continuing controversy and some skepticism. Indeed, of the major countries that at one time embarked on commercial MHD programs, Great Britain, France, and the Federal Republic of Germany sharply curtailed their efforts, while Japan, Poland, the United States, and the Soviet Union are continuing their programs on a relatively large scale. One of the major reasons for the decline in interest is the relative unavailability and cost of fossil fuels, especially coal, for central station power generation.

SPECIAL APPLICATIONS

As an energy device, the MHD generator has characteristics -- e.g., compactness, simplicity, and high power density -- which make it especially suitable for a variety of special applications, particularly in the military area. This realization came early in the engineering development of MHD in the United States, and by the late 1950s, several programs exploring special applications were initiated. Major emphasis was placed on MHD for space-vehicle applications, based on the observations that MHD generators could operate at higher temperatures than mechanical turbines with consequent savings in radiator weight and that, apart from the flowing gas itself, the MHD system involved no moving components. It was claimed that the construction of a static ducting system would, a priori, lead to better reliability than might be expected from highly stressed, high-speed, high-temperature turbines. For the U.S. space program, the most clearly identified goal was to use MHD as the conversion system in a nuclear electric system of 300-kW output to supply electric power for interplanetary deep-space probes. Difficulties in matching MHD to ultra-high-temperature gas-cooled reactors and the availability of the SNAP-50 reactor led to the concentration of a major effort on liquid-metal systems of the condensing-cycle type, although considerable study was also applied to closed-cycle plasma systems.

The United States has considered MHD for ship propulsion since 1960; here compactness and the absence of intermediate rotating machinery were felt to be important from the viewpoint of reducing noise, especially in

submarine turbines. Work was first concentrated on gas-cooled reactors with nonequilibrium, closed-cycle MHD generators, but the difficulty of finding a suitable reactor-MHD combination has led to increasing interest in liquid-metal MHD systems for this application [4].

MHD applications in other areas of U.S. defense technology have, until recently, been less easy to justify. A number of efforts were undertaken, however, which contributed significantly to the development of MHD technology. Early defense interests were in the area of space power systems, especially for space platforms, which would require substantial amounts of electric power. The concept here again was to use a nuclear heat source, with the cycle depending on the application involved. An open-cycle nuclear system was shown to be feasible where relatively short bursts of power (up to about one hour) are required; chemical fuels are suitable for even shorter times. For longer power requirements, it was proposed to use a closed-cycle system similar to that considered for deep-space applications.

With the support of the Defense Advanced Research Projects Agency, the Avco-Everett Research Laboratory designed, built, and put into operation in 1963 the first large MHD generator. Known as the Avco Mark V, it produced 32 megawatts of electrical power for a few seconds [5].

A related development was the proposal to use MHD to provide the electric power necessary for the magnetohydrodynamic acceleration of a gas stream in a hypersonic wind-tunnel facility. This concept led to the construction of the first MHD pilot-scale facility at the Arnold Engineering Development Center in Tullahoma, Tennessee [6]. The generator, known as the LORHO, was designed for 20-MW-under-peak operating conditions and actually achieved a peak power of 18 MW for about 10 seconds. It can be viewed as a model for all emergency MHD systems for both commercial use and special applications. (The LORHO is described in more detail in Section IV.)

There has been a continued and determined effort to develop compact MHD generators for airborne applications. The justification in this case is based on compactness, availability of DC outputs without the need for rotating machinery and rectifiers, particularly in sizes over about 5-MW electric output. The largest program involving this application considered

the use of MHD on tactical aircraft for battlefield illumination (Project Brilliant) [7]; current interest is strongly directed toward providing power for electric laser systems. The use of the MHD principle to produce population inversion in a flowing gas laser is an alternative to the separate MHD-laser combination.

A separate class of MHD applications broadly related to the LORHO pilot concept was in the area of power accelerators and thermonuclear-fusion devices. Again, the system argument is based on the ability of MHD to deliver large blocks of power for short periods.

The historical evolution of the Soviet special-applications MHD program is difficult to determine. It is likely, however, that the USSR considered similar applications and drew the same conclusions the United States did.

USSR programs in liquid-metal MHD apparently evolved at about the same time as in the United States -- the early 1960s. Information on these programs began to surface in the open literature at the time of the Salzburg International Symposium on Magnetohydrodynamic Electrical Power Generation in 1966. At that Conference it was revealed that programs for the development of liquid-metal MHD were being carried out at a number of locations; the most prominently mentioned were the Kurchatov Institute of Atomic Energy, the Institute of High Temperatures, the Krzhizhanovskiy Power Institute, and the Institute of Physics of the Latvian SSR. Since then, other institutes and laboratories that were or still are involved in liquid-metal MHD have been identified in discussions with staff at conferences and in publications, including: the D. V. Yefremov Research Institute for Electrophysical Equipment in Leningrad, Leningrad Naval College, Moscow Aviation Institute, Leningrade State University, Moscow Physicotechnical Institute, Kiev Institute of Electrodynamics, and Kiev Institute for Heat Physics.

## INTERNATIONAL COOPERATION

The international character of MHD research and development deserves special mention here. The international MHD community has been prominent in promoting information exchange, and this exchange simplifies the task of preparing a comparative overview of MHD technology with respect to

the United States and the USSR. MHD has also been the subject of direct exchange between U.S. and Soviet scientists and is a major item in the recently negotiated Cooperative Program in Energy under the auspices of the U.S.-USSR Joint Commission of Scientific and Technological Cooperation. This development is specifically mentioned in the June 1973 energy message sent to the Congress by President Nixon.

The proposed U.S.-USSR MHD program -- which *involves open-cycle MHD only* -- has as its ultimate goal, according to the U.S. view, the design, construction, and initial operation of one or more commercial-scale MHD facilities in each country. The program stipulates:

1. Exchange of technical information
2. Joint theoretical and experimental research
3. Cooperative design of MHD power plants
4. Evaluation of the feasibility of joint construction and initial operation of a commercial-scale MHD plant.

The specific activities anticipated under each of these four major headings were agreed on at the first meeting of the U.S.-USSR Standing Steering Committee for the Scientific and Technical Cooperative Development of Commercial-Scale Open-Cycle MHD Power Plants, held in Washington in July 1973 (see Appendix for the record of this meeting).

The International MHD Liaison Group has also been instrumental in establishing ties between U.S. and Soviet MHD specialists and has provided some insights into the Soviet program that could not have been easily attained otherwise.

## II. MHD TECHNOLOGY REVIEW

The development of MHD generators had its origin in thermodynamic, rather than electromechanical, considerations and specifically in the factors governing the performance of a heat engine and the rejection of waste heat. From the performance viewpoint, the improved efficiency of conversion of heat into useful work, given by the Carnot principle for an ideal heat engine, indicates that it is profitable to utilize source temperatures of up to about 5000° K when the heat rejection temperature is at normal ambient levels. Going much beyond 3000° K, however, is usually not justifiable because of diminishing returns -- e.g., at 3000° K the Carnot efficiency is .90, at 5000° K, it is .94. However, actual system comparisons must be made on the basis of real thermal efficiencies of alternative systems, and the temperature argument, although it illustrates the gains available from high temperature systems, is insufficient to establish the performance of systems on a comparable basis. Heat engines are usually thought of in terms of producing mechanical work through the interaction between an expanding working fluid and moving solids. Such systems are clearly temperature-limited by the materials from which the actual energy collection surfaces are made; the most optimistic estimates for turbines do not exceed the working gas temperature of 2000° K. Thus, a substantial temperature range exists above that of existing heat engines, provided a new technique for energy conversion can be identified.

This is supplied by the MHD generator, which might better be described as an "electromagnetic turbine." In it, the expanding working fluid, which is now hot enough to be electrically conducting, interacts with a magnetic field to produce a mechanical force of electromagnetic origin. Thus, energy is extracted from the working fluid without moving surfaces. It is, of course, motional electromagnetic induction that is the origin of the force on the gas and that gives the MHD generator the unique capability among heat engines of delivering its output work directly in electrical form. The electrical conductivity is usually that of thermodynamic equilibrium (i.e., all species of the working fluid are at the same temperature), but in certain cases the conductivity can be enhanced via hot electrons (new equilibrium conditions).

It cannot be emphasized too strongly that the MHD generator must be assessed in terms of its performance as a heat engine that converts heat energy into electrical form. In principle, it will operate with any heat source that can provide the necessary inlet temperature and, as a turbine, has the potential to provide higher overall thermal efficiencies than any competing turbine system.

There is, however, one other aspect of the high-temperature operation of heat engines which is important as a background to the material presented in this Report. The preceding argument is of greatest significance for terrestrially based power systems. In the case of space power systems, where a heat engine is contemplated for conversion purposes, the launch weight, especially of the radiating system for waste heat rejection, becomes a primary concern. Thus, a turbine capable of operation at high temperatures is required to minimize radiator weight. Here again, the electromagnetic turbine has potential advantages.

The MHD generator is a part of high-temperature heat-engine technology: Its successful operation depends on the resolution of identifiable turbine performance and materials requirements, and its overall performance depends on the system in which it is embedded as the energy-conversion device. Finally, the heat source with which it is associated depends on the intended application and on the availability of high-temperature heat sources compatible with MHD technology.

The interaction between an electrically conducting gas and an electromagnetic field involves a volume process which distinguishes the MHD generator from mechanical turbines where blading surfaces must be provided. Losses depend on MHD generator wall area; thus, performance is improved as the output power is increased, i.e., as the volume-to-surface ratio increases. The electrical power level at which MHD becomes attractive depends on heat source conditions, but in no case is it less than about one megawatt.

The startup time of an MHD generator is basically set by the time taken to fill the generator working volume with ionized gas at the required velocity, that is, in excess of 500 meters/sec; thus, basic generator startup in milliseconds or less is possible, and actual system startup times are determined by the heat source, materials, and checking procedures.

MHD HEAT SOURCES

In principle, the electromagnetic turbine can operate between arbitrary source and sink temperatures, but most working fluids appropriate for heat engines do not become sufficiently electrically conducting until they have attained temperatures of the order of 8000° K. Accordingly, some method is required to "seed" the working fluid, except in the case of metal vapors, which show adequate conductivity upwards of about 2000° K.

One seeding method, resulting in what is often referred to as "plasma MHD," involves the introduction of small amounts of an alkali metal, potassium and cesium being preferred because of their low ionization potential. At temperatures above about 2500° K, this seed material is completely ionized thermally and provides the electrons required for plasma conductivity. In the case of monatomic gases, these electrons can attain temperatures significantly higher than that of the working gas and, under these nonequilibrium ionization conditions, adequate conductivity is possible down to temperatures as low as 1500° K.

A quite different approach to gas seeding is to introduce a liquid metal in sufficient quantity to form a two-phase flow comprising a liquid-metal matrix with trapped gas or vapor bubbles. This arrangement is limited only by the melting and boiling points of the liquid selected (usually an alkali metal) and the availability of containment materials and is typically considered to be suitable in the range of 800° to 1300° K. Beyond 1300° K, volatility problems become serious.

Plasma MHD needs a heat source temperature of at least 2500° K for thermal ionization and 2000° K for some extrathermal mechanisms. It can be recognized immediately that naturally occurring or distillate fossil fuels, burned either with oxygen or compressed, preheated air, can attain the required temperatures for all plasma MHD systems. A nuclear heat source of the gas-cooled variety is also a possibility, at least for nonequilibrium ionization, as has already been demonstrated by the performance of the Nerva nuclear-rocket engine and by the predicted performance of ultra-high-temperature gas-cooled reactors. However, a

nuclear MHD system implies a major heat source development, whereas with fossil fuels the heat source situation is much more straightforward.

Since a liquid-metal MHD system involves separate gas and liquid-metal streams which are mixed only in the generator interaction region, it is possible to add heat to either stream. This in turn indicates that either a gas-cooled or a liquid-metal-cooled reactor can act as the heat source. High temperature gas-cooled reactors currently under development represent a potential heat source, and possible extensions of liquid-metal-cooled, fast-breeder-reactor technology to temperatures above 800° K would provide a temperature range beyond the capability of the steam turbine but entirely suitable for liquid-metal MHD systems.

Other heat sources of a more speculative kind should not be overlooked in connection with MHD systems. The gas-core reactor removes the limitations associated with solid-fuel-element operation at high temperatures and provides a working gas for MHD generators in the appropriate temperature range. The use of lithium in fusion reactors may provide a possibility of operating either a liquid-metal system or, if lithium vaporization is possible within the fusion reactor, a plasma system based on lithium vapor as the working fluid. Finally, interest has recently been expressed in the possibility of using solar-derived heat to raise the MHD working substance to the requisite temperature range.

In all of the foregoing, it has been assumed that direct burning of the primary fuel (either chemical or nuclear) is used to obtain the necessary temperatures for the MHD working fluid. However, the derivation of a synthetic fuel using a nuclear source of process heat provides yet another situation in which MHD generators may be utilized. In the so-called hydrogen economy, an MHD generator operating on water vapor derived from hydrogen combustion with oxygen is yet another way in which the MHD processes may be utilized as the heat-to-electric-energy conversion mechanism.

This review of the variety of heat source possibilities for MHD generators has been included both to emphasize the energy conversion aspect of MHD and to dispel the notion that somehow MHD systems are related to coal and are in competition with nuclear-power systems. The

situation is summarized by observing that MHD generators, being heat engines, are in competition with other energy-conversion technologies such as gas turbines, alkali-metal-vapor turbines and steam turbines, as well as with nonthermodynamic processes such as fuel cells. MHD will be successful if it can show advantages with respect to other energy-conversion technologies.

## MHD CYCLES

Much has been written on the many alternative MHD cycles and these will only be briefly reviewed. A major distinction is between open- and closed-cycle systems in which the working fluid is used on the once-through basis or recycled to the heat source, respectively. The operation of MHD generators directly on combustion products is an obvious application of open-cycle systems, but an MHD generator operated with a Nerva-type nuclear heat source can also be operated on an open-cycle basis.

While the selection of the open cycle is an obvious choice in the case of combustion gases and enables the heat source and the MHD generator to be thermally connected without any intervening heat transfer surface, a nuclear reactor using solid-fuel elements requires the selection of a working fluid which has the following three properties: (1) must be capable of providing heat transfer under reactor operating conditions; (2) does not require excessive compressor work; and (3) is not rendered active within the reactor (otherwise an intermediate primary cooling loop would have to be used to contain the radioactive products). Helium most nearly fits all of these requirements and, as already explained, can give a substantial increase in electrical conductivity at the upper limit of reactor gas-stagnation temperature (around 2000° K) due to nonequilibrium ionization.

## PLASMA INSTABILITIES

The establishment of nonequilibrium ionization conditions has the consequence that a relatively fast-growing instability can develop under plasma conditions representative of MHD-generator duct requirements. The mechanism for electron heating is provided by the electric currents in

the gas, termed Joule heating. If the electron density increases in any part of the plasma, the conductivity will increase locally, causing the current density to increase in that part of the plasma, and this increase, in turn, further increases the electron density. The process continues until the region cannot support further increases; then it transfers to another location. This fluctuation results in electromagnetic turbulence, which like its fluid counterpart, increases energy losses (mainly because the average electrical conductivity of the plasma is less than predicted by simple theory). It is possible, however, to design a satisfactory generator despite these instabilities, as has been demonstrated by General Electric.

Instabilities are otherwise of little concern to MHD plasmas -- certainly far less than in the case of fusion systems, the reason for this being that MHD involves primarily dense, collision-dominated plasmas in thermodynamic equilibrium. The Hall effect can generate acoustic waves, known as magnetoacoustic waves, but the growth rates are slow relative to the fluid transit time in MHD-generator ducts, and it has yet to be shown that these waves significantly degrade MHD-generator performance.

## COMMERCIAL APPLICATION OF OPEN-CYCLE SYSTEMS

The origin of the combined cycle concept for electric power generation lies in the limitation of the steam turboalternator with respect to boiler-tube materials which can meet the pressure and temperature conditions required by thermal efficiencies in excess of 40 percent. It appears that, for all practical purposes, the performance development of steam-turbine systems has reached its upper limits, and only by combining steam cycles with other conversion systems can significant increases be obtained. The MHD generator falls naturally into the highest temperature range where it is worthwhile to operate heat engines and contain the working fluid with materials which do not involve excessive thermal losses. It is to be noted that MHD generators are not associated uniquely with steam turbines. The combination of MHD with gas turbines is also an attractive possibility that is receiving attention.

To achieve the efficiency potential of MHD for central-station power generation, it is necessary to embed the MHD unit in a relatively complex cycle, the essential features of which are shown in Fig. 1; Fig. 2 shows the overall cycle flow. Compressed, preheated air is used as an oxidizer to achieve the necessary flame temperatures, with the preheater being charged from the generator exhaust. A simpler cycle alternative, which avoids the problem of charging the air heater with ash- and seed-laden combustion gases, involves the use of a separately fired heater; however, this introduces a small thermodynamic penalty. The necessary flame temperatures can also be obtained using oxygen enrichment; it has been estimated that oxygen costs would have to be less than about $4 per ton before this would be economically competitive with the use of preheaters [8].

Many cycle analyses have been conducted on binary MHD-steam-plant cycles and complete agreement has been established on the expected overall performance and the needed component specifications. It is necessary to operate the generators with a magnetic field in the range of 4-6 Tesla (advanced generators may operate at higher fields), and it has been shown that this field can be obtained economically only with a superconducting magnet. The steam generator required is of a somewhat different design from that employed in conventional power plants, because of the high temperature of the MHD generator exhaust, the presence of ash, seed, and slag in the combustion products, and the need to control the decomposition of the high $NO_x$ levels found in MHD combustors. Another important component required by an MHD system is an inverter to couple the DC output of the MHD generator to AC power lines. Experience has been gained -- almost all of it in the USSR -- in operating MHD generators through an inverter system. It is anticipated that the inverters will be similar to those developed for asynchronous links in long-distance-electric-power-transmission lines.

Cycle analyses have generally established that the operation of first-generation-MHD combined cycles will lead to efficiencies in the range of 48-52 percent with preheat temperatures around 1500° K, and that later improvements in all aspects of MHD technology can raise this

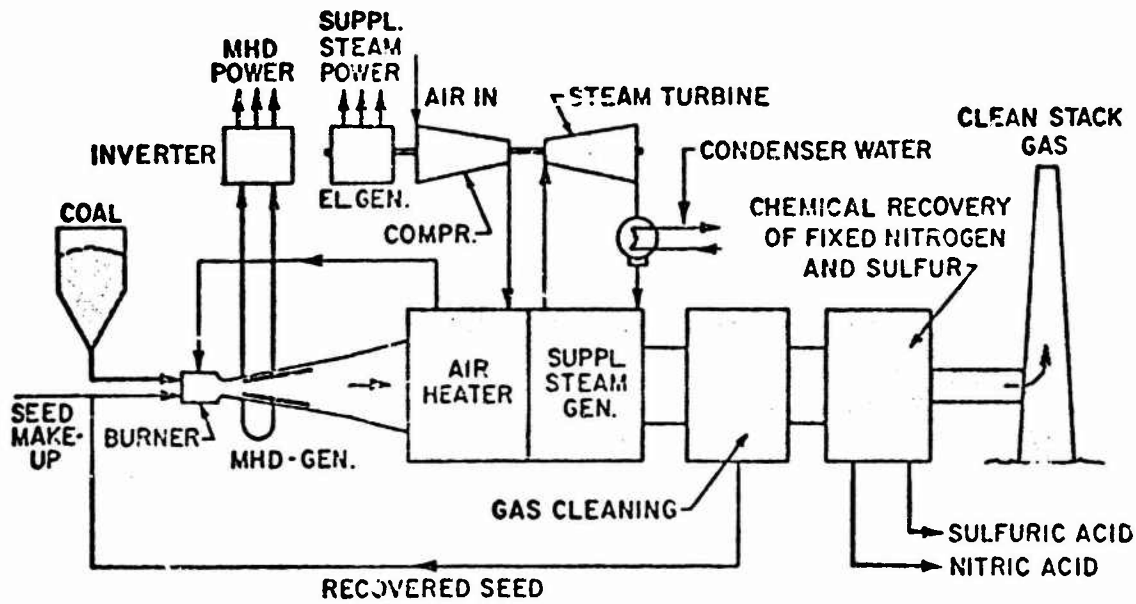


Fig. 1a -- MHD steam cycle [8]

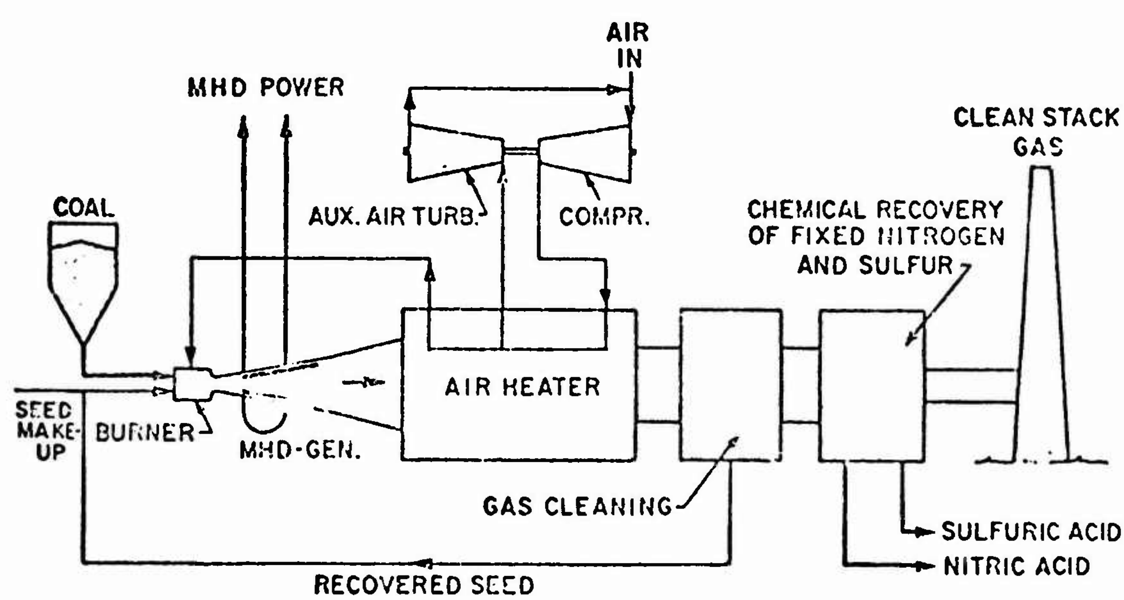


Fig. 1b -- MHD air-turbine cycle [8]

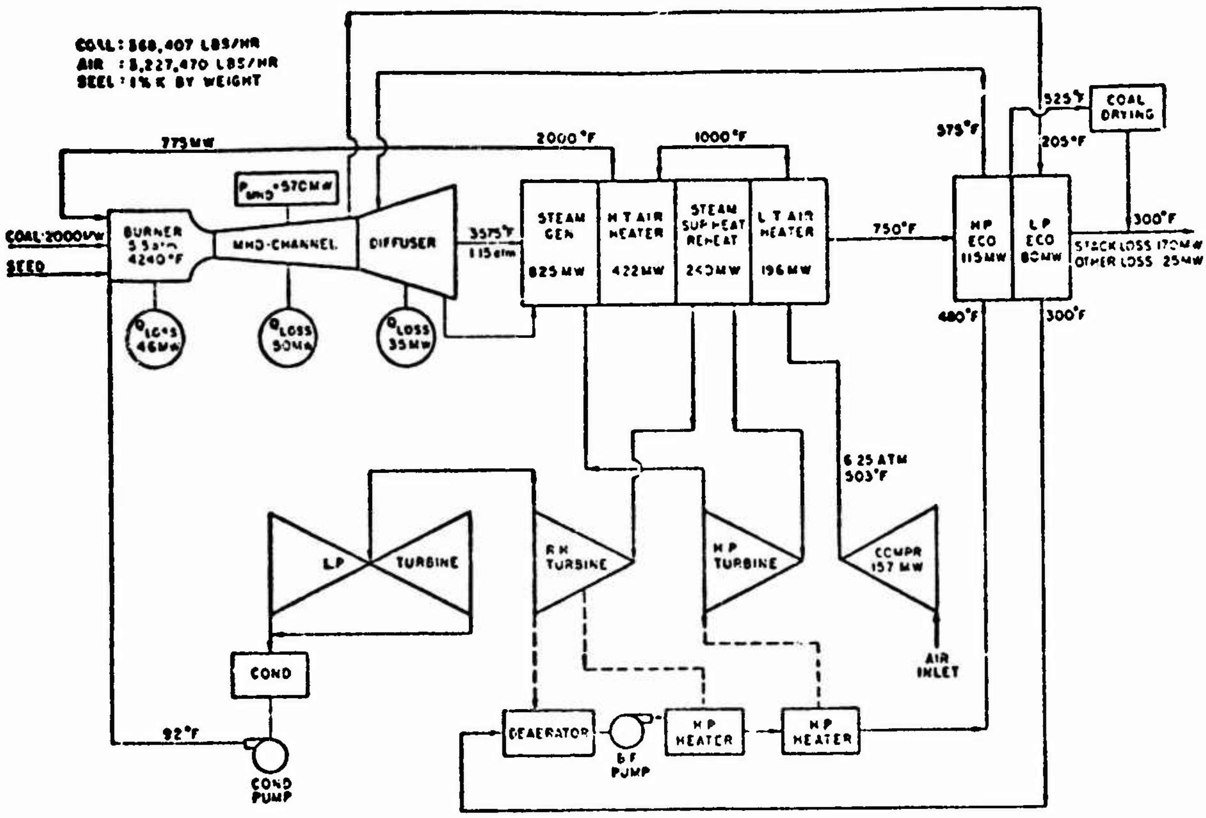


Fig. 2 -- Overall cycle-flow diagram [8]

overall efficiency to beyond 60 percent. It has been found that about half of the electrical power is generated by the MHD unit and the balance by the steam part of the cycle. The performance of the MHD generator is expected to improve with advancing technology, and this will raise its share of the total output to around 70 percent. The main function of the steam cycle, then, is to drive the air compressor, and the consequence of technology improvements is to increase the utilization of the high-temperature end of the thermodynamic cycle for electric-power generation.

To the extent that economic evaluations can be made in advance of the development of a technology, the costs of MHD-steam-power plants have been shown to be competitive with those of corresponding conventional fossil-fired plants when the cost of pollution control is

included. Because of higher efficiency and, therefore, better fuel utilization, operating costs are less. The bus-bar costs of electricity generation by MHD is generally projected to be as much as 20 percent lower than conventional fossil-fired plants can achieve. Although the economics of MHD must remain in some question until further advance of the technology has been made, the observation that the steam plant provides about 50 percent of the electrical output also implies that the components involved are either conventional technology or represent only small modifications of existing practice. Thus, about half the electrical capacity of the plant can be priced rather accurately; the chief uncertainties are in the MHD unit, particularly in the superconducting magnet and the preheaters. The simplicity of the MHD ducts and the straightforward construction of the diffusers lead to the conclusion that these terms are a relatively insignificant part of the total cost.

In addition to efficiency and cost considerations, MHD has been viewed favorably for commercial applications because of its pollution-control features. The overall thermal efficiency obtainable implies a reduction of thermal pollution which, for advanced MHD cycles, is about four times that of the present light-water-reactor nuclear plants for a specified electrical output. With MHD combined with a gas turbine as a bottoming stage, the need for steam condensation is eliminated, and waste heat is exhausted directly to the atmosphere. The situation with respect to air pollution is more complex, but it turns out that several of the requirements for successful MHD operation also serve to reduce the emission of both particulates and noxious chemicals. The recovery of the seed material is required on economic grounds, and this, through systems of filters, separators, and precipitators, guarantees a high level of particulate removal. Though the high temperatures at which MHD operates lead to the formation of large concentrations of oxides of nitrogen (typically 10,000 parts per million), the dwell time of combustion gases in the steam generator can be arranged to be long enough to ensure that, at all times, the $NO_x$ is close to an equilibrium condition. This leads to rapid decomposition and to the achievement of $NO_x$-emission levels which, when the efficiency of the plant is taken into account,

should be substantially below those required by the Environmental Protection Agency. The latter conclusion is, of course, based on the assumption that the extended Zeldovich mechanism is adequate for $NO_x$ finite rate modeling, which it probably should be. Another useful consequence is that the seed material, essential to render the gas electrically conducting, also serves as a sulfur collector. It is usually proposed to inject into the combustor potassium carbonate which disassociates at the temperatures involved. When recombination occurs, the potassium preferentially combines with sulfur to form $K_2SO_4$. This can then be removed and reprocessed into $K_2CO_3$ in a simple chemical system which recovers sulfur in its elemental state.

The central question regarding the utilization of MHD as an energy-conversion device in baseload-commercial-power generation is the future of fossil fuels for this type of station. About ten years ago, a prominent view was that light-water reactors would provide the technology base and experience for nuclear power and that liquid-metal-cooled fast breeder reactors would be available as an advanced system to utilize the unconverted natural uranium left over from water-reactor operation, as well as to breed new fuel and maximize utilization of available uranium supplies. Uncertainties with respect to the timetable of breeder development, questions as to the extent of accessible uranium resources, public concern for the development of nuclear power on a large scale, increasing energy demands, and limited nuclear-industry capacity have all led to a modified position in which it is now conceded that, even if nuclear systems come on line at an optimum rate, fossil fuels will play an extensive role in electric-power generation for at least several decades to come. However, as this is the time which it will take to develop MHD for baseload service, a long-range commitment to utilize fossil fuels for electric-power generation is needed if MHD is to be widely used in baseload service.

The successful development of nuclear systems for baseload service would still leave intermediate (2000-4000 hours per year) and peaking (less than 2000 hours per year) loads to be met by other technologies, since nuclear plants are not suitable for cycling (i.e., load variation), on both technical and economic grounds. At present, intermediate loading is covered by older fossil stations, but as demand increases, new

stations will be required for this service; here MHD has a further important commercial application, since either fossil or synthetic fuels (and probably oxygen) will be utilized. It should not, therefore, be concluded that MHD is a candidate only for baseload service; intermediate load and possibly peaking may be of greater significance.

The utilization of MHD for emergency service (up to 100 hours per year), peaking applications, and intermediate loads continue to receive substantial attention. In the case of emergency service, the argument for MHD is based on the simplicity of the equipment, the capability of operating in large unit sizes (unlike the gas turbine), and most important, the ability to make rapid starts to full power. This rapid startup feature has also figured prominently in arguments supporting MHD for military applications, and indeed, the demonstration that it can be achieved was originally made with military applications in view. If a large MHD unit for commercial network service could indeed achieve full power in 10 to 15 seconds, this would qualify it as "spinning service," such as is currently maintained in large rotating machinery. Emergency MHD systems would be of the simplest kind, consisting of only a burner, distillate fuel, pure oxygen as the oxidizer, a channel and magnet assembly, a diffuser, a scrubber, and an inverter system. The use of distillate fuel avoids any problems from sulfur dioxide, the selection of pure oxygen as the oxidizer eliminates any significant $NO_x$ formation, and downstream scrubbing removes all seed materials. Thus, a clean exhaust is obtained without any additional pollution control equipment. Capital-cost predictions for these simple emergency units have shown competitive values of installed costs with respect to gas turbines, particularly when the size advantage of MHD is taken into account. However, the need for oxygen adds significantly to operating costs, and the competitive range for this type of MHD appears to be less than about 200 hours per annum.

To increase the availability of MHD, it has been proposed to add downstream limited-temperature air heaters using metallic tubular construction, an air compressor, and closed-cycle gas-turbine drive. With these additions, oxygen would serve only to enrich air and may even

be eliminated if an advanced preheater is employed. The effect of these additions is to increase the time range of MHD into peaking and intermediate service. The high cost of oxygen thus far has been the main factor in producing unfavorable economics in the peaking range However, the combination of MHD with a gas turbine for intermediate service is more promising; further work on this is required to establish its real potential, especially when the environmental advantages of eliminating steam turbines are taken into account.

It is appropriate to observe in conclusion that the utilization of electromagnetic turbines implies that a working fluid of high temperature and high available enthalpy is generated. Inasmuch as this type of power generation requires various high-temperature technologies, the capital cost can be expected to be considerably higher than in the case of simpler, low-temperature equipment, although the cost is partly offset by the lower thermal capacity, and therefore physical size, required to achieve the specified electrical output. In baseload and intermediate service, where high-capital-cost equipment has the best opportunity to achieve economies through maximum utilization of plant capacity, high-temperature-conversion schemes appear to be most attractive. At the other end of the time scale, the ability to deliver large blocks of power on short demand is a valuable asset which emergency MHD promises to meet economically. Thus, MHD emerges as a power system having as its primary characteristics high efficiency and rapid startup, these being separately applicable to different energy-demand situations.

Closed-cycle plasma and liquid-metal MHD systems with nuclear-heat sources have also been proposed for central-station-power applications, and good technical progress has been made with the generators themselves. However, lack of parallel commercial reactor work has inhibited their development. Certain types of liquid-metal MHD systems eventually might be tied to the LMFBR and HTGCR currently under development. Recently, the use of a fossil-fuel heat source has also been proposed to enable these systems to be utilized commercially [9].

## CLOSED-CYCLE SYSTEM AND SPECIAL APPLICATIONS

Whereas commercial applications of MHD are attractive from an energy-conversion-efficiency viewpoint and have mainly involved open-cycle systems with combustion products in the MHD generator, special applications of MHD evolved from its unique performance characteristics, and a variety of working fluids have been considered. Among the most frequently cited advantages of MHD generators in the special applications environment are the following:

1. very rapid startup
2. construction simplicity
3. increasingly favorable specific weight as output power increases (as direct consequence of the volume-to-surface effect)
4. ability to operate at high temperatures
5. compactness as a thermal-to-electric-energy convertor

There are three types of MHD systems that are commonly included in the special applications category:

1. rocket-driven and explosive-driven open-cycle
2. nuclear-heated closed-cycle plasma
3. closed-cycle liquid-metal

Both closed-cycle plasma and closed-cycle liquid-metal systems are closely linked with nuclear-heat sources and space and shipboard (silent-running engine) applications.

The rocket-driven MHD generator takes advantage of the similarities between a rocket engine and an MHD combustor to create a compact, lightweight, extremely simple MHD system that is, at the same time, capable of high power densities. Because of the MHD system's high operating temperature, high-plasma conductivity, cleanliness of the working gas, design simplicity, and limited duration of operation, the development problems associated with its application appear to be substantially less serious than those related to central-station power systems.

In the explosive-driven MHD generator, a seeded, shaped charge is used as the propellant to produce enormous power densities (hundreds of MW per $m^3$) for very short periods (up to 1 msec). This high power density is achieved through high temperatures and the correspondingly high conductivity generated by the constituents of the shaped charge.

## III. U.S. AND USSR TECHNOLOGY-DEVELOPMENT APPROACHES

In contrast to the U.S. program which, partly by design, but als partly because of Department of Defense applications interests, developed MHD generators on a high-power, short-time basis and utilized small facilities for the selection and testing of candidate materials (the so-called two-axis approach), the visible Soviet program concentrated on pilot-plant development. The Soviets reasoned that a small installation involving all of the components of an MHD system should be put into operation first, both to test materials on a long-duration basis and to determine the problems of interconnecting the various components. The Soviets built the U-02, a small-scale, complete MHD pilot plant, and concentrated on its integrated operation. This approach had, however, an important inherent limitation: It did not allow the Soviets to control separately the experimental parameters of each major component for the purpose of component optimization, nor did it provide the experience of significant MHD effects in generator ducts.

In terms of national energy policy, they had the considerable advantage of a plentiful supply of natural gas and so could develop MHD directly for this fuel along what is usually assumed to be the most straightforward technological approach. In his most recent U.S. visit, however, Sheindlin indicated that this approach is being changed. The USSR now plans to conserve natural-gas resources and, like the United States, to proceed directly to coal-firing as soon as it is practicable.

After some success with the U-02 installation and, secondhand, the U.S. experience in the operation of large generators, notably the Avco Mark V, the Soviets decided, probably in 1966, to proceed to a full-scale pilot plant. This decision was apparently motivated, to a large extent, by the need for a relatively large-scale technology to ensure visibility for the Soviet MHD program. Once locked into a technology development, the Soviet MHD advocates apparently reasoned, it would be difficult for their authorities to terminate or modify the program. Thus, the Soviet MHD community now has the world's first MHD pilot plant, the U-25

installation. This contrast in technology development and the availability of natural gas as a fuel in the USSR have made Soviet MHD development a very different activity from its United States counterpart.

Little information is available on MHD development work by the Soviet military establishment. There has been some reference to MHD for ship propulsion, Arctic icebreakers being used as an example of the type of vessel involved.

On the U.S. military side, two large generators -- the Mark V and the LORHO -- constituted important technology demonstrations and contributed greatly to the development of a viable MHD-generator technology. By the mid-1960s, Air Force efforts were concentrated on the development of airborne MHD. The cancellation of Project Brilliant caused a drop in MHD activity and interest in the Department of Defense comparable to the collapse of commercial interest when the Avco utility-pilot-plant program failed to obtain support. The postponement or cancellation of space programs involving the need for large amounts of electrical power led to the curtailment or termination of work on various aspects of closed-cycle MHD. The only new program initiated by the Air Force Systems Command, through the Aero Propulsion Laboratory at the Wright-Patterson Air Force Base, was designed to lead to a 10-MW prototype MHD unit for Air Force service.

Experimental MHD facilities in the United States, especially at Avco, have been developed in accordance with what has often been called the two-axis approach to MHD: Generator development is undertaken at increasingly large output powers, but for quite short operating times (generally a few seconds to one minute). Steady-state fluid flow is obtained in a millisecond, and one minute of operation is thus more than adequate for checkout and measurement on large-scale machines.

Generator development (electrical output is plotted along the y-axis of a power-time plot) at power levels of about 100 kW to 30 MW has provided detailed information on generator operation and, even with the relatively short operating times involved, on materials. The major materials development, however, was conducted on small-scale facilities (equivalent to 10-kW electrical output or less) operating for up to 200 hours (Avco obtained three months of cumulative experience). Materials

testing of both generator channels and auxiliary components at low power for extended times constitutes the other axis (x-axis) of MHD development and is still continuing.

The Soviet Union, far more than the United States, has stressed materials development and has used its U-02 facility extensively as a test bed for new materials. A wide range of materials were studied [10-18], but as yet there appear to have been no significant breakthroughs. In 1972, the Institute of High Temperatures began working on fiber-reinforced composites -- a most promising type of material -- for MHD applications [19].

There is presently no U.S. work on open-cycle, high-power, short-duration generators, but this is planned for resumption in the near future. In the U.S. program, the first time that high power and long duration will be attempted simultaneously will be when a pilot plant begins operation.

The philosophical difference between the Soviet and U.S. approaches has put the two programs in quite different positions at the present time. As was stressed in the Introduction, the MHD generator is an electromagnetic turbine, and it is only through sufficiently attractive performance of that turbine that MHD systems can be justified. The realization of these systems then becomes a matter of finding materials that will serve for the required periods of time under the environmental conditions imposed by the MHD system. There are two basic MHD development approaches that can be followed: (1) the so-called progressive plant basis, or (2) the integrated plant basis -- i.e., either the generator can be developed separately (independent of system constraints) and later placed in a system environment, or the entire system can be developed as a single integral unit. The United States chose the first approach; the Soviets chose the second. While the Soviet approach does have the advantage of providing a complete pilot plant test bed, it makes for great difficulties in the optimization of individual components; thus the United States has at the present time a substantially advanced understanding of component operation, particularly high-performance generators, relative to the Soviet groups. The Soviet investigators, however, have the experience of integrated plant operation.

National fuel situations have also led to quite different development considerations in the United States, the Soviet Union, the European

Economic Community countries, and Japan. For the Soviet Union, the availability of natural gas has so far made this the preferred fuel for MHD development, and only modest attention has been given to coal firing. In the United States, however, the abundance of coal as a fuel reserve has led to the concentration of efforts on coal-fired systems so far as baseload operation is concerned. The need to import oil for electric-power generation and the high cost of coal has led all of the EEC countries to abandon their MHD development efforts. In Japan, although there is heavy reliance on imported fuel, MHD continues to be developed vigorously as an alternative power strategy to a totally nuclear economy.

The described U.S. open-cycle approach, however, may be in the process of being revised. From 1968 to 1971, outside of two university programs, MHD activity concentrated on systems evaluation and program planning. Of the several studies undertaken, that of the panel set up by the Office of Science and Technology (OST) in 1968 was by far the most significant in the commercial MHD area. In 1969 the Panel issued a favorable report [20] which recognized that earlier efforts towards the development of MHD for central-station power generation had not concentrated adequately on the difficult problems of coal firing; accordingly, the report recommended a research and development program devoted to those problems where the engineering data required for pilot-plant design and construction were lacking.

Based on this report and with support from members of the Congress, the Department of the Interior, through its Office of Coal Research (OCR), received a small budget for MHD development in FY 1971; this amount was increased to about $5,750,000 in FY 1974 [21]. With this appropriation, OCR has been able to embark upon a program following roughly the outlines of the OST recommendations and now has twelve contractors working on different aspects of coal-fired commercial MHD systems.

An important aspect of the OST report was the recommendation that the electric-utility industry evaluate its position with respect to MHD and contribute to any development program that it (the industry) agreed to support. To this end, the Electric Research Council (ERC) appointed a Task Force on MHD which examined MHD technology from the utility industry viewpoint and recommended that the industry cooperate with the government on an MHD development program. With the assistance

of the OCR, the ERC Task Force commissioned the Massachusetts Institute of Technology to prepare an MHD-technology assessment and to recommend a plan that would implement the OST report and carry MHD through the pilot-plant stage. At this time, no final agreement has been reached, either within the utility industry or between this industry and the government, on the plan that should be followed. In addition to the MIT proposal, a number of other plans were prepared privately.

The electric utility industry also examined its R&D goals for the rest of this century, and, in 1971, outlined an MHD-development plan to make MHD available for commercial service by 1985 [22]. A National Program for MHD Central Power Generation was drawn up in 1973 on the basis of the industry's outline, some of the ideas of the MIT report, and suggestions from the MHD community [23]. Figure 3 gives an overview of the proposed Program; Fig. 4 and Table 1 show its cost. The Program, which progresses through the stages of further research and development, a pilot plant, and finally, a demonstration plant, shows that under the most favorable circumstances MHD can be made available by 1985 at a cost in the vicinity of $0.5 billion. Adoption of this plan and its successful execution would make it possible for a significant amount of new, installed electrical capacity to utilize MHD generators by 1990 with consequent lower fuel consumption and environmental benefits.

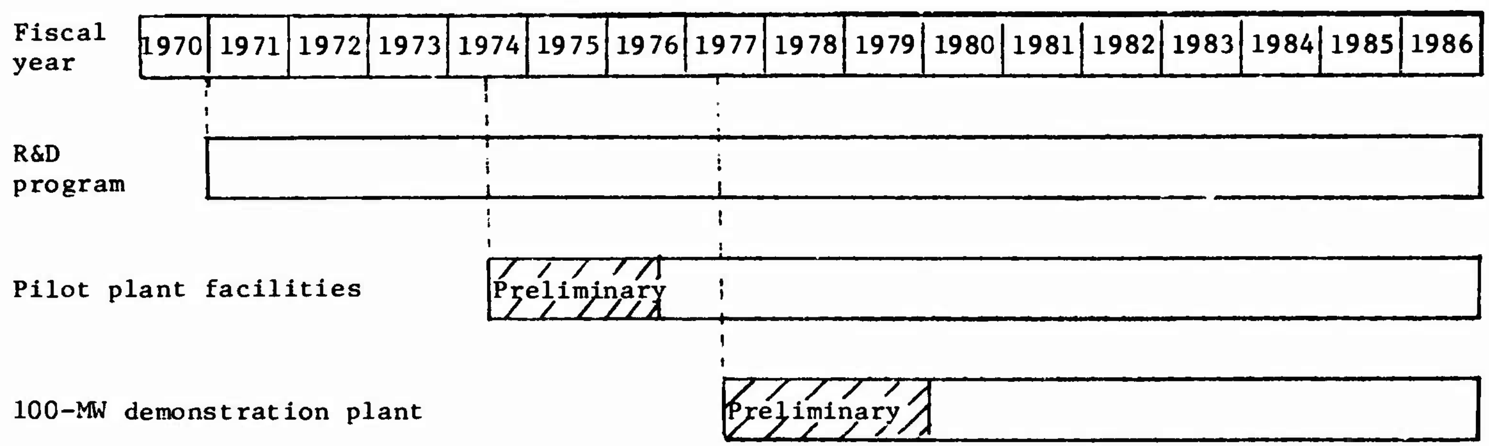


Fig. 3 -- Proposed national MHD-development program [23]

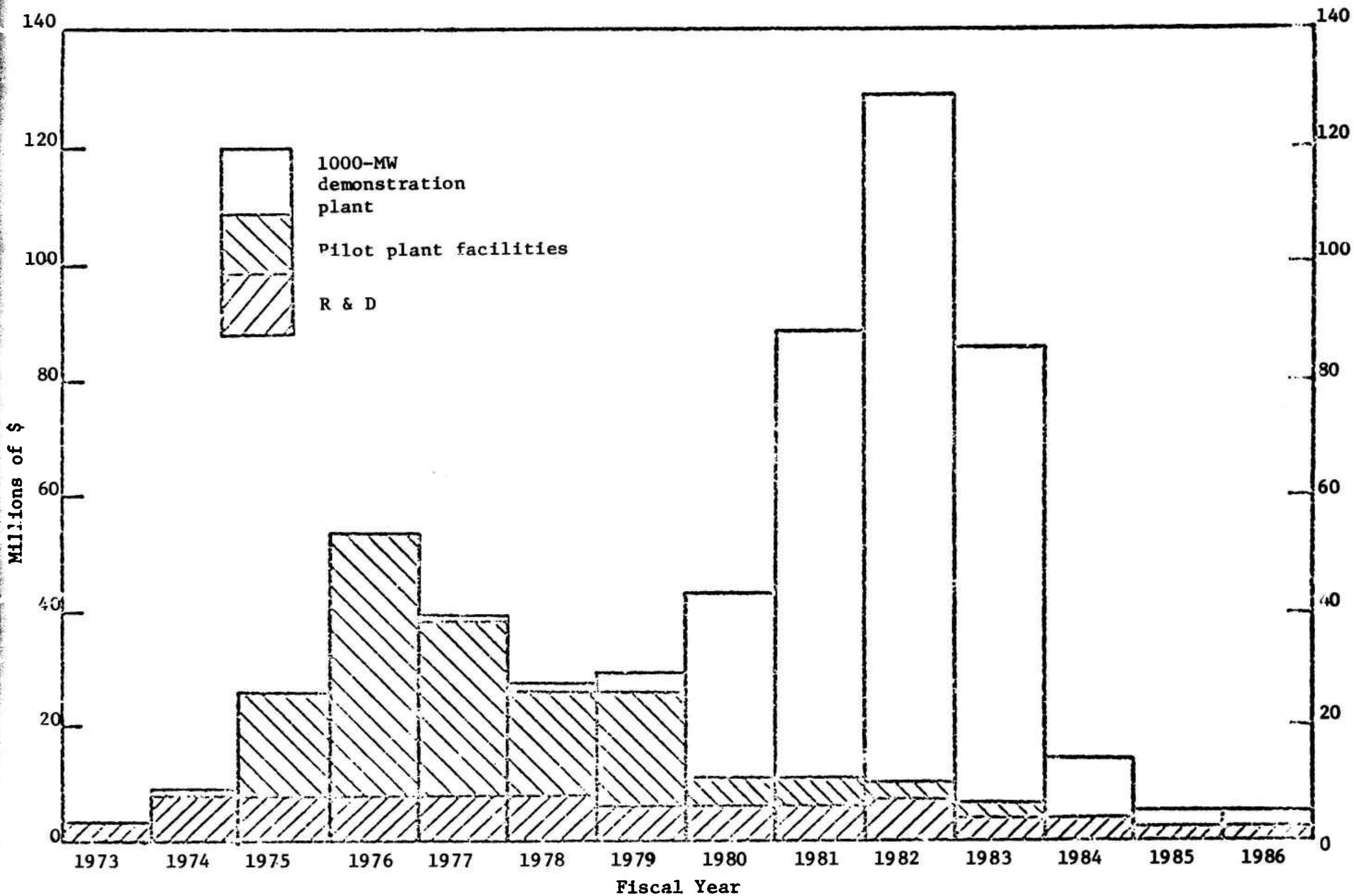


Fig. 4 -- MHD-Development-Cost Plan [23]

Table 1

MHD-DEVELOPMENT-COST PLAN [23]
(in millions of 1973 dollars)

| Fiscal year | R & D program | Pilot plant facilities | 1000-MW demonstration plant | Yearly total |
|---|---|---|---|---|
| 1973 | 3.0 | | | 3.0 |
| 1974 | 7.0 | 1.0 | | 8.0 |
| 1975 | 8.0 | 18.0 | | 26.0 |
| 1976 | 8.0 | 46.0 | | 54.0 |
| 1977 | 8.0 | 29.0 | 1.0 | 38.0 |
| 1978 | 8.0 | 18.0 | 1.0 | 27.0 |
| 1979 | 6.0 | 20.0 | 3.0 | 29.0 |
| 1980 | 6.0 | 5.0 | 34.0 | 45.0 |
| 1981 | 6.0 | 4.0 | 78.0 | 88.0 |
| 1982 | 7.0 | 2.0 | 120.0 | 129.0 |
| 1983 | 4.0 | 2.0 | 80.0 | 86.0 |
| 1984 | 4.0 | | 13.0 | 17.0 |
| 1985 | 2.0 | | 3.0 | 5.0 |
| 1986 | 2.0 | | 3.0 | 5.0 |
| Sum | 79.0 | 145.0 | 336.0 | 560.0 |

| | |
|---|---|
| Gross cost of program ............. | 560.0 |
| Less sale of power ................ | 25.0 |
| Less residual worth of plant at one-half construction cost ....... | 125.0 |
| Net cost of program ........... | 410.0 |

## IV. COMPARISON OF MAJOR MHD INSTALLATIONS

### OPEN-CYCLE

Nothing is known of the early MHD facilities in the USSR. Available reports suggest that the first significant Soviet installation was the U-02 [24-26] -- a small-scale model of a complete MHD pilot plant, shown in Fig. 5a and 5b. This facility was designed and built by the Sheindlin

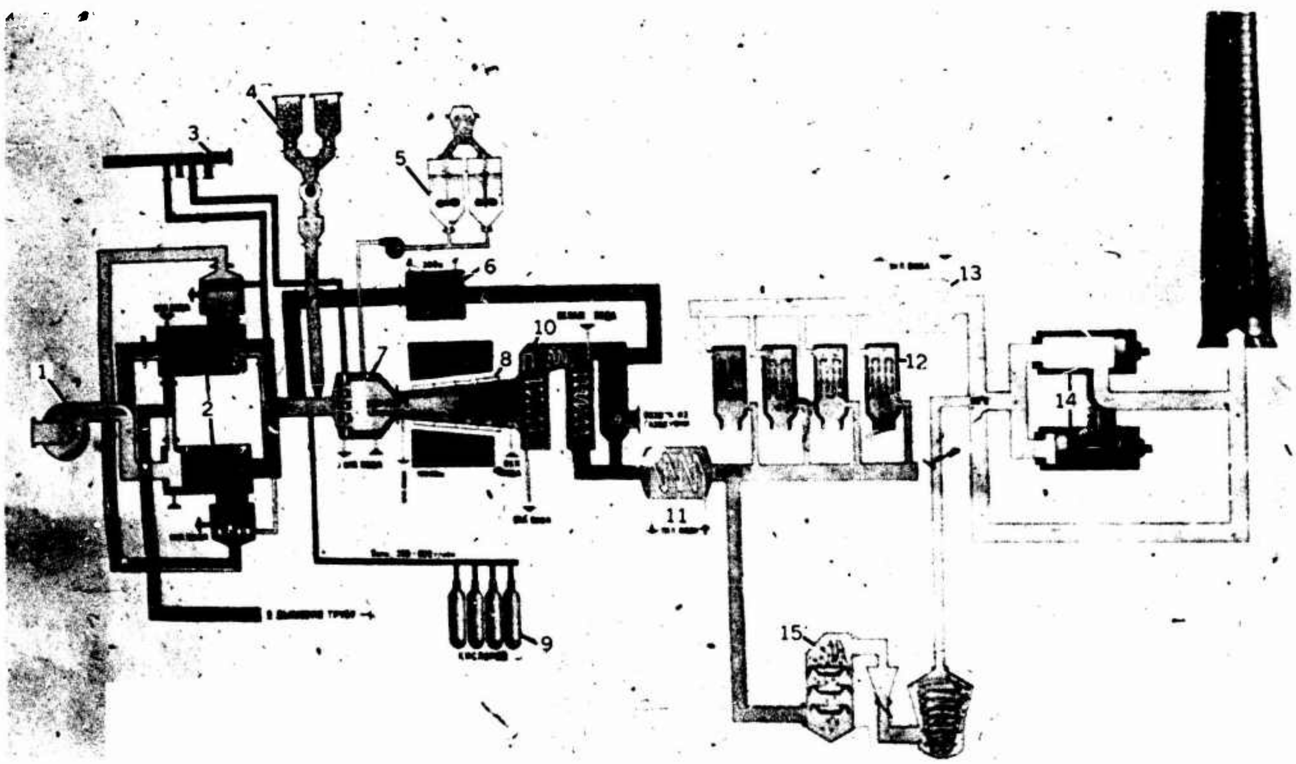


Fig. 5(a) -- U-02, Stage 1 [24]

1 - air compressor
2 - regenerative air heater
3 - gas-feed system
4 - seed-injection system (dry)
5 - seed-injection system (wet)
6 - low-temperature heater
7 - combustion chamber
8 - MHD channel
9 - oxygen-injection system
10 - steam-generator simulation
11 - water-coolant system I
12 - dry filters
13 - water-coolant system II
14 - vacuum pumps
15 - wet-scrubbing system

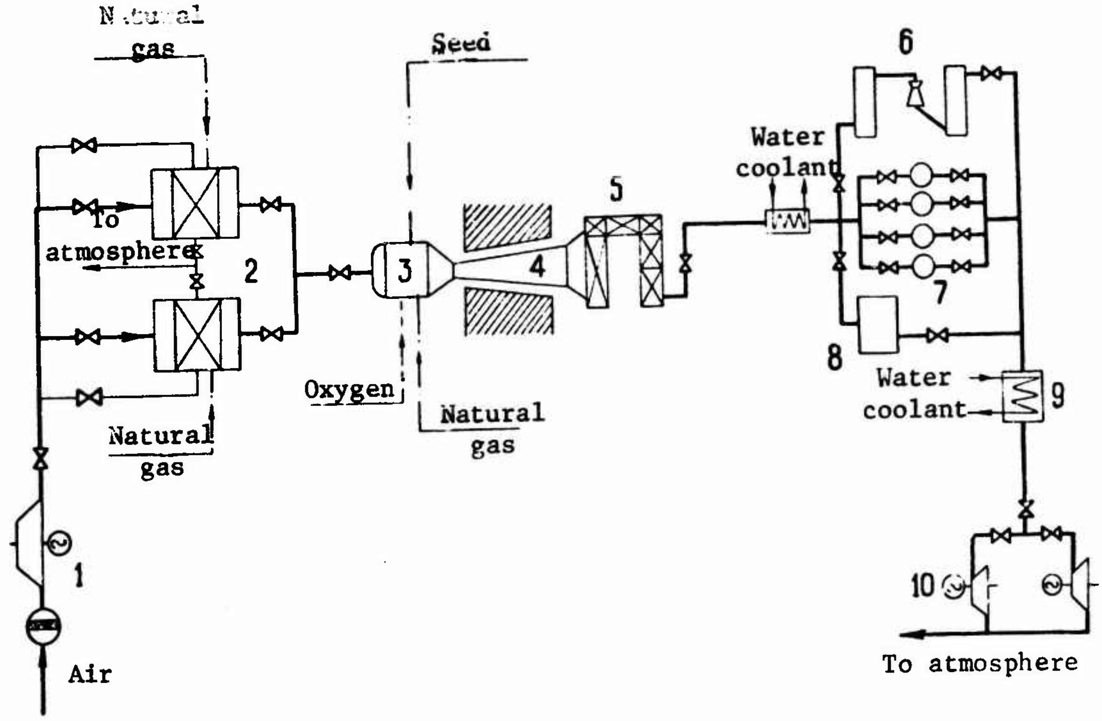


Fig. 5(b) -- U-02, Stage 2 [24]

1 - blower
2 - high-temperature air heater
3 - combustion chamber
4 - MHD channel
5 - steam-generator simulation
6 - seed-recovery system (wet)
7 - seed-recovery system (dry)
8 - experimental electrostatic filter
9 - heat exchanger
10 - vacuum pump

group at the Institute of High Temperatures. The U-02, with its mass flow of 1 kg/sec and electrical output of around 60 kW, enabled the Soviets to obtain a vast amount of materials experience, but because of their inability to manipulate individually the experimental parameters of their major components, it did not provide the needed exposure to generator problems.

The U-02 is installed in a former tramway power station across the Moscow River from the Kremlin. It uses natural gas, and enriched, preheated air as the oxi zer. The major components in sequence are a pair of air heaters fired separately to raise the oxidizer to a temperature

of 1900° K. Combustors of various configurations and wall conditions (hot and cold) have been tested; seed can be injected into them either in powder form or as a saturated solution. The MHD-generator duct itself, operated subsonically in a magnetic field of 1.7 Tesla, has not yet achieved the level of sophisticated generator-channel construction long since universally adopted by U.S. experimenters. The duct is followed by a simulated steam generator in which boiler tube materials have been tested for many thousands of hours. The installation ends with, first, wet scrubbing and dry bag-filter systems for the exhaust gases and, second, an exhaust fan prior to the stack. Electrical power is supplied to the AC line through a solid-state inverter system; thus, in 1966 the U-02 became the first installation ever to supply any MHD-generated power to a commercial AC network [3, 24, 27].

In the United States, the development of inverters for other applications has significantly increased confidence that these can be introduced into the MHD system when sufficient progress has been made in more crucial components. For the Soviets, however, the inclusion of an inverter is a natural part of their plan to develop a complete model installation, and in justifying the success of MHD, they indicated privately that the ability to deliver power to the line was of great importance to the Ministry of Electrification.

The decision to proceed with the next stage of commercial, industrial-scale development of the pilot plant was made in 1966, with the basic requirement that the plant -- the U-25 -- be big enough to have an overall thermal efficiency at least equal to that which could be obtained with a plant of the same size using conventional steam-turbine machinery [1]. A total output of 75 MW was selected, with the calculated overall efficiency set at 33 percent, which is about the value for a conventional steam plant of 75-MW output. A schematic drawing of the overall U-25 facility is presented in Fig. 6, followed by cross-sectional views of the MHD and steam components in Figs. 7 and 8, respectively.

The MHD generator itself was estimated in 1966 to be capable of delivering an electrical output of 25 MW (about 55 percent turbine efficiency) under its most optimistic and advanced design conditions; it is driven by a combustor supplied with natural gas and enriched, preheated air (Fig. 9). Later, more sophisticated calculations showed that the maximum attainable

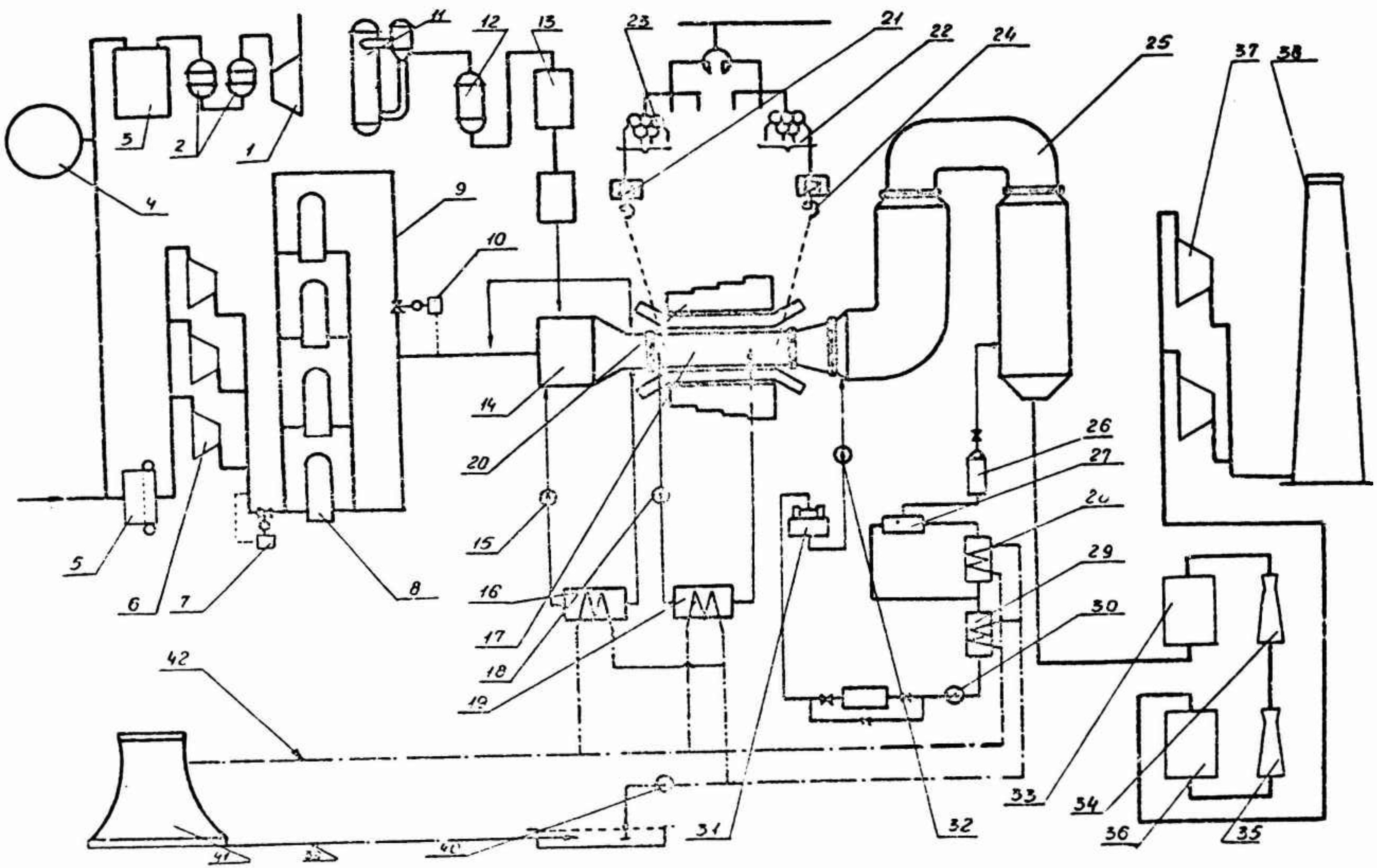


Fig. 6 -- U-25 diagram [28]

1 - turbocompressor; 2 - nitrogen-water cooling system; 3 - air separator; 4 - gas tank; 5 - rotating filter chamber; 6 - centrifugal air injector; 7 - automatic regulator; 8 - air heater; 9 - heated air duct; 10 - automatic regulator; 11 - evaporator; 12 - [omitted in original]; 13 - injector; 14 - combustion chamber; 15 - coolant-water pump for combustion chamber; 16 - heat exchangers; 17 - MHD channel; 18 - coolant-water pump for MHD channel; 19 - heat exchangers; 20 - magnet poles; 21 - inverter; 22 - inverter connections; 23 - transformer; 24 - reactor; 25 - once-through steam generator; 26 - cooler; 27 - startup/discharge separator; 28 - condensers; 29 - condensate coolers; 30 - pump; 31 - atmospheric deaerator; 32 - electric feed pump; 33 - foam unit; 34-35 - two-stage turbulent gas scrubber; 36 - cyclone water droplet separator; 37 - centrifugal exhausters; 38 - smoke stack; 39 - nonpressurized discharge; 40 - process water pumps; 41 - wet cooling tower; 42 - pressurized water pipes

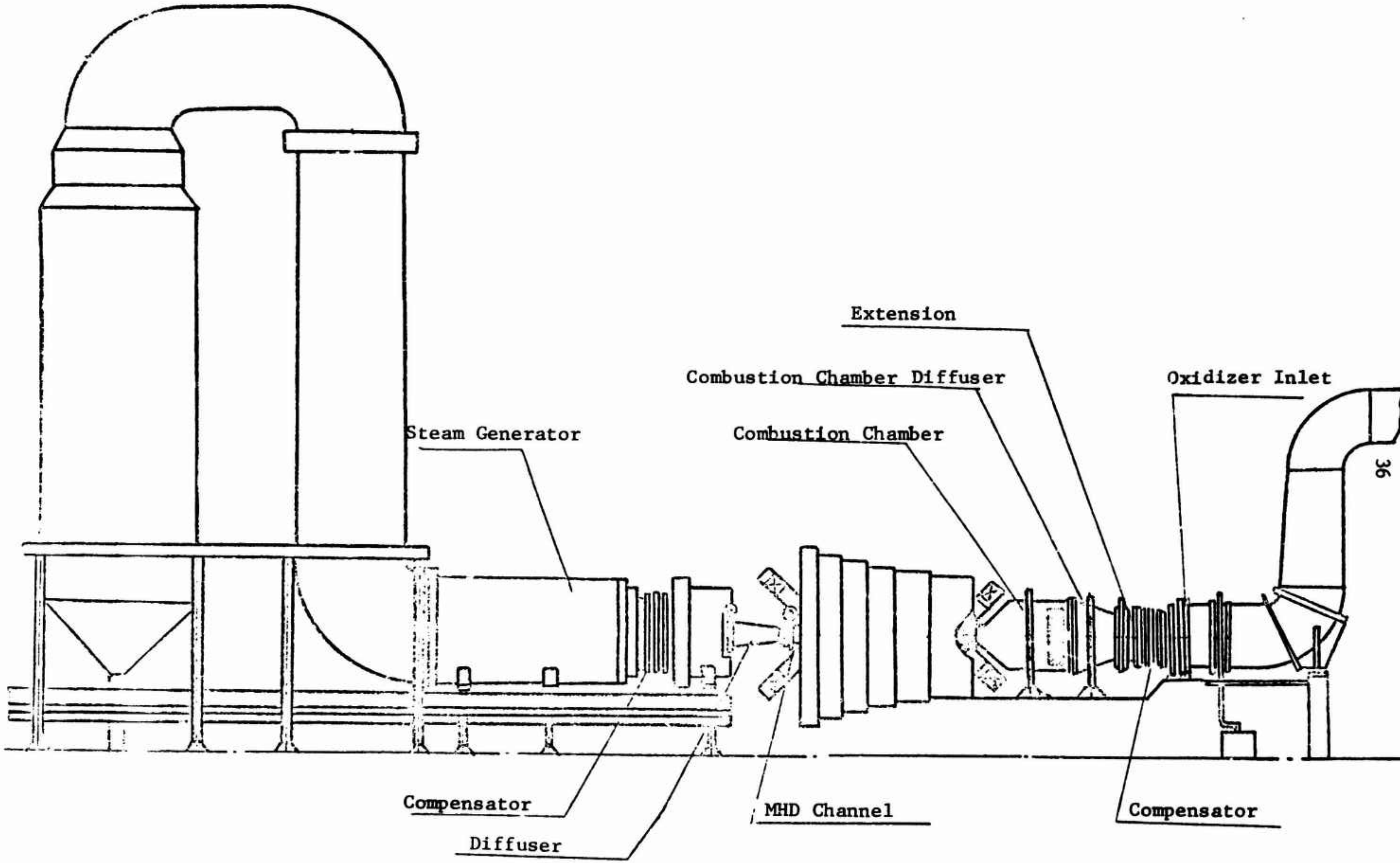


Fig. 7 -- U-25 MHD generator [28]

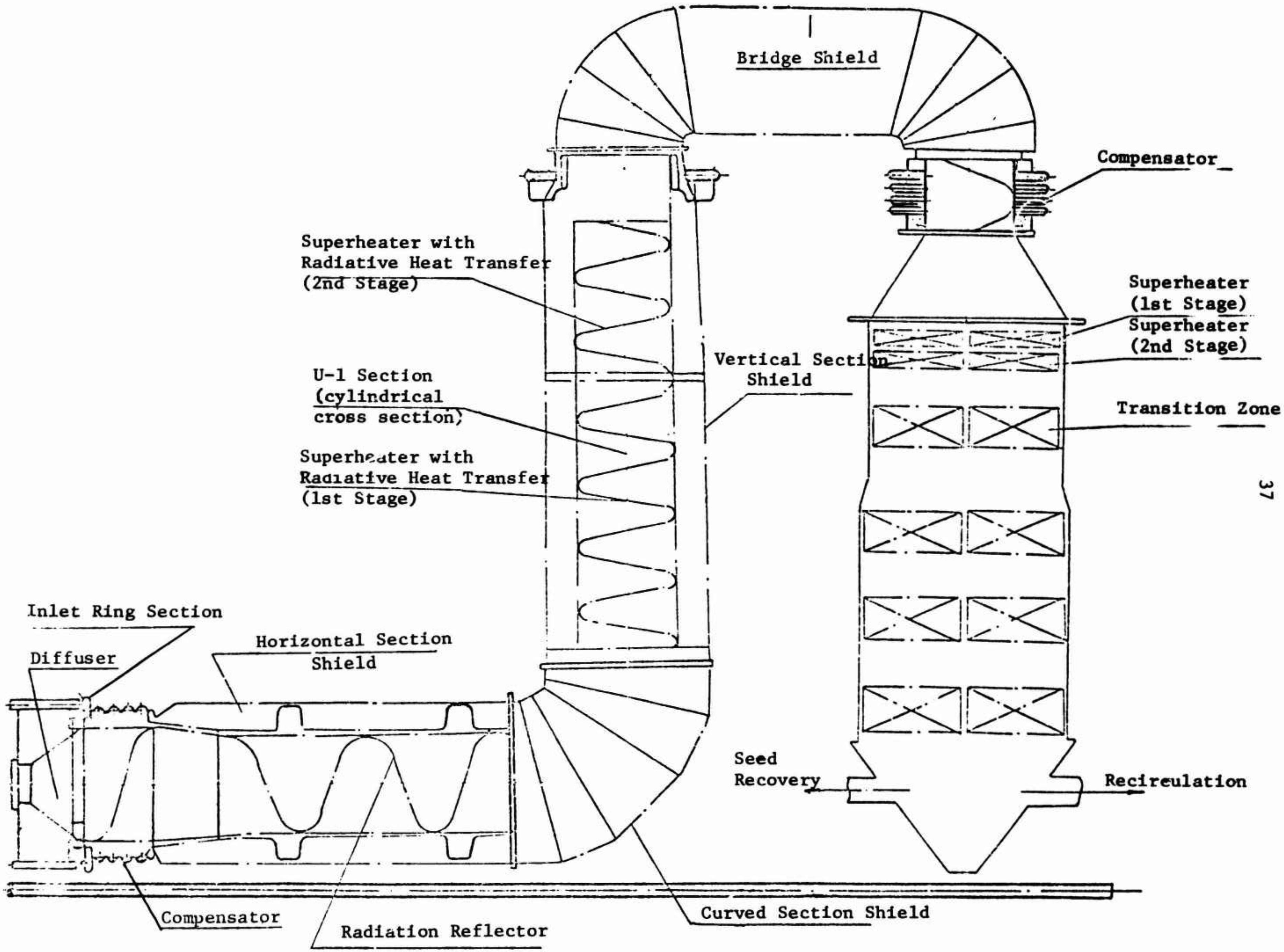


Fig. 8 -- U-25 steam generator [28]

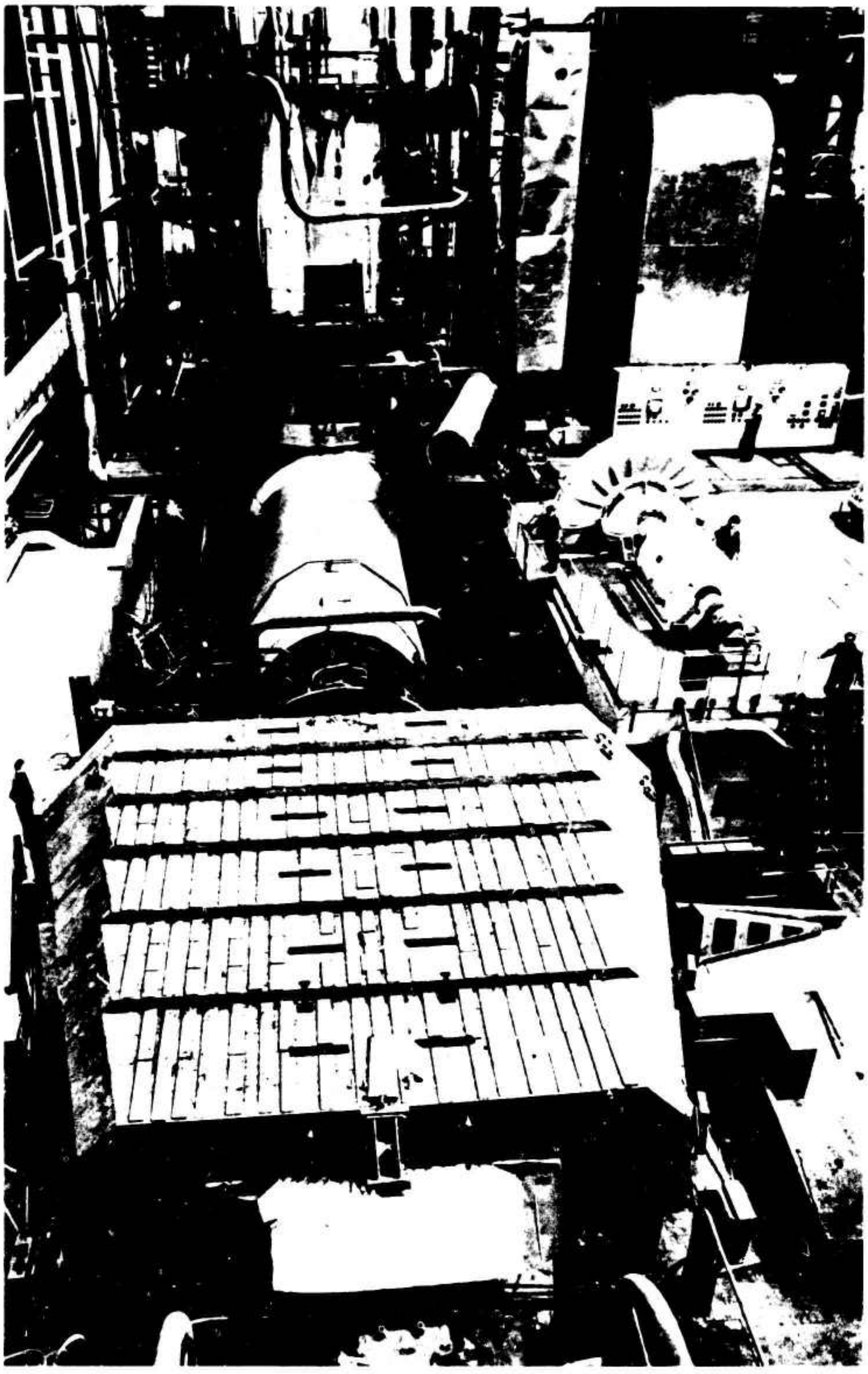

Fig. 9 -- U-25 MHD generator (with steam generator in background)

electrical output is only 15 to 17 MW. The preheaters are not of the advanced type used in the U-02, but are of the Cowper type (based on conventional Soviet steel-mill practice), which preheat the oxidizer to 1500° K. Figure 10 is a photograph of the plant, with the huge preheaters in the foreground. A particularly impressive part of the U-25 installation is the steam generator (Fig. 11) which immediately follows the MHD generator. This steam generator is made up of radiative and convective portions having ingenious design features. The U-25 installation also has both wet and dry scrubbers and mercury valve inverters. The generator channel is about five meters long and involves a massive, 2500-ton electromagnet which produces a field of about 2 Tesla. The designers clearly chose to utilize existing technology wherever possible, and the plant design is not in any way venturesome. In contrast to designs proposed for pilot plants in the United States, the generator itself is also of a very simple design. It has been pointed out by a number of MHD people that the lack of Soviet experience with large generators is evident in the design selected [28-34].

Sensors are used extensively in the U-25 to monitor ongoing processes, and a two-computer system is used to sort and analyze obtained data (see Fig. 12) [28]. It is interesting to note that the computers used in the data processing phase -- the Ural-14 and the Hewlett Packard 2116 (see Fig. 13) -- are not known to have been used previously by the Soviets in this way. The Ural-14 is one of the newer, second-generation Soviet computers (first produced in the mid-1960s). It is a fixed-point, single-address binary computer, capable of operating at 10,000 opns/sec. It has a core store of 8 K (augmentable to 64 K) 24-bit words, with a cycle time of 9 microsec. It can process seven problems simultaneously and handle up to 24 external units in a variable configuration; circuit control is used for data storage, transfer, and processing [35].

The HP-2116 is a 16-bit-word, 1.6-μsec-cycle-time minicomputer with a core memory augmentable to 32 K. The export of American minicomputers is not restricted, and it appears that Hewlett Packard sold one or more HP-2116's directly to the Soviets via their Geneva office at a cost of roughly $40,000 per unit. Production of the HP-2116 model, first built in 1970 using integrated circuit CTL logic, was discontinued last year. The primary function of the HP-2116 in the U-25 data processing system

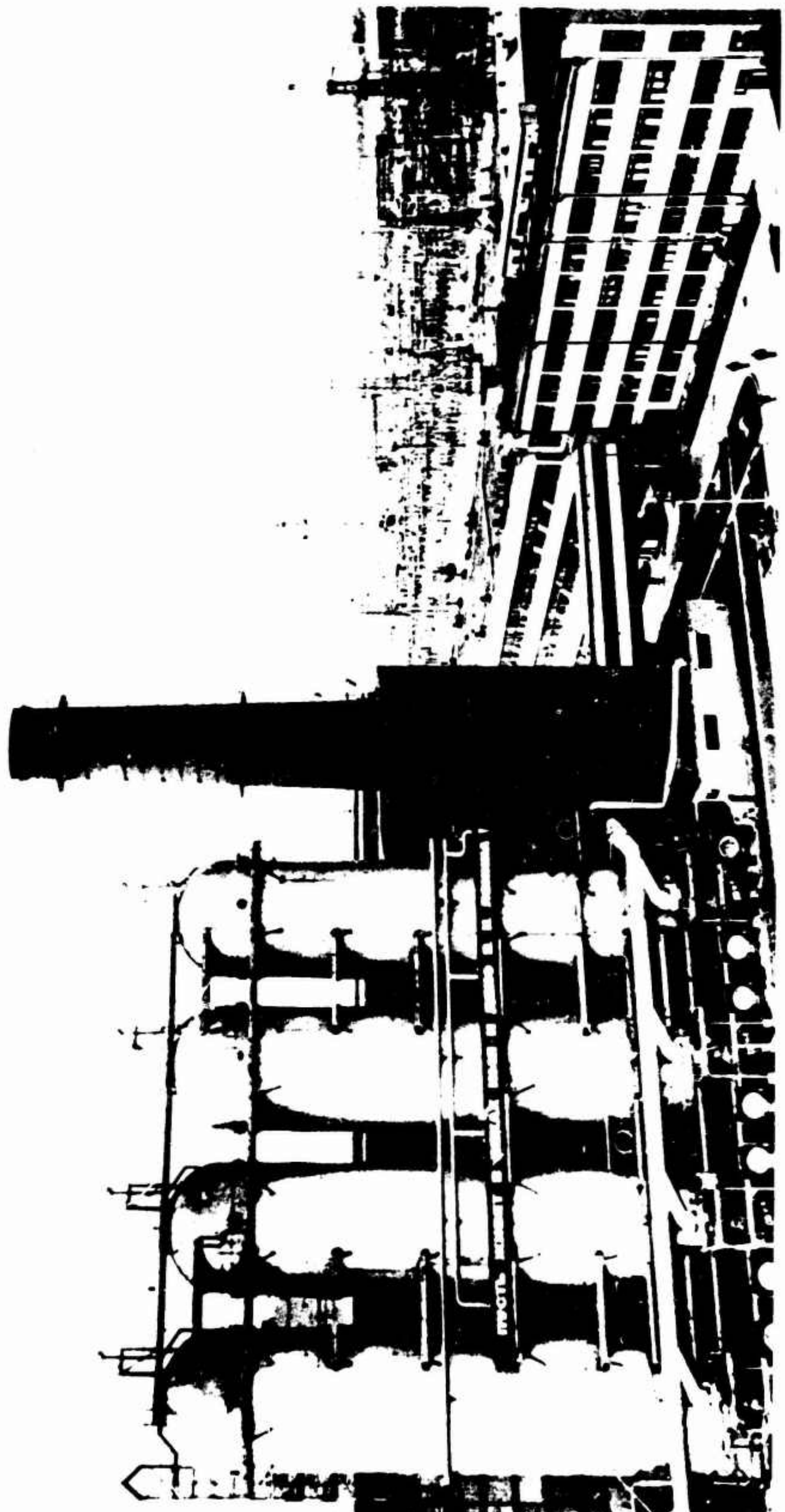

Fig. 10 -- External view of the U-25

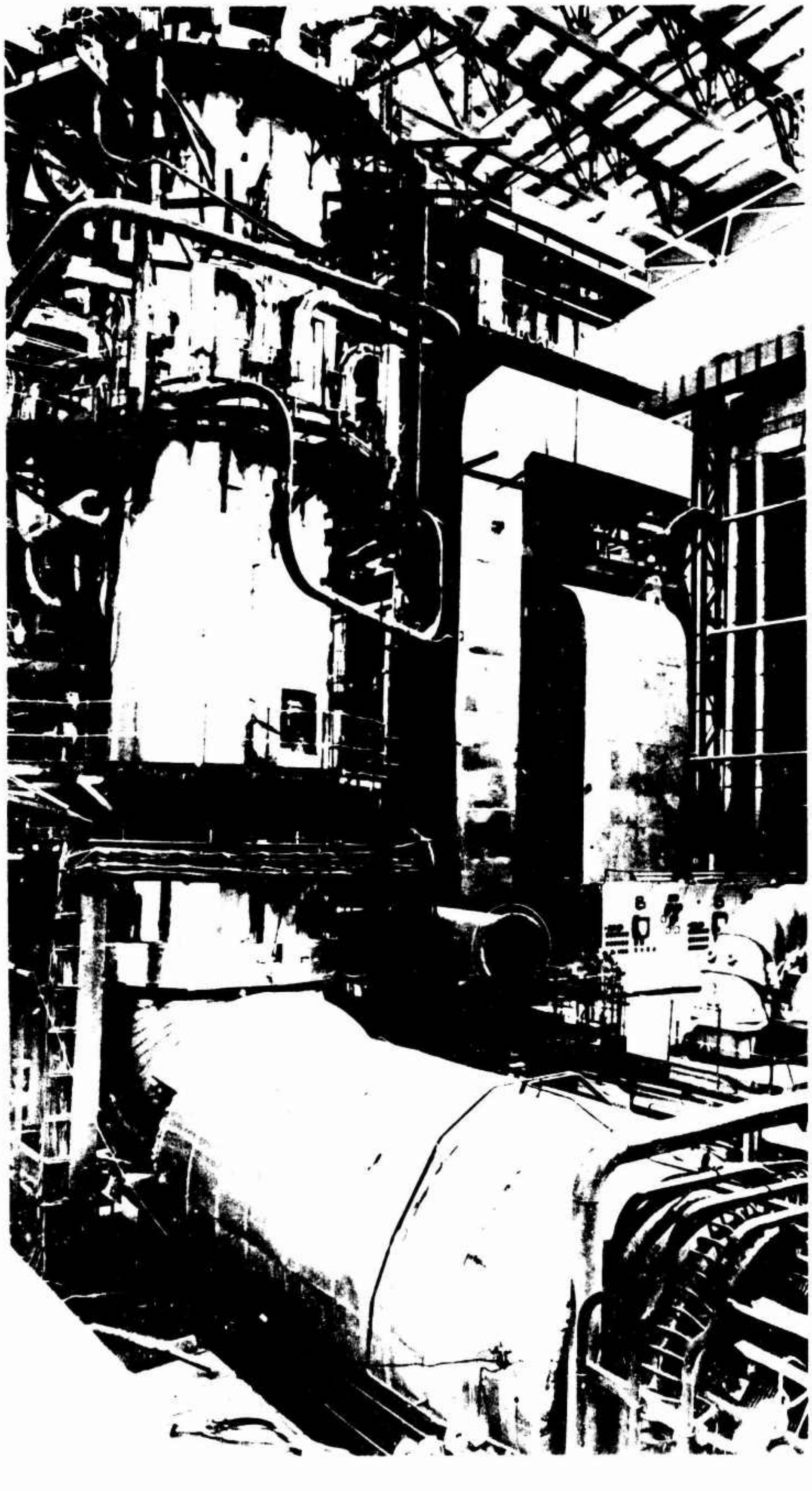

Fig. 11 -- P-25 steam generator [28]

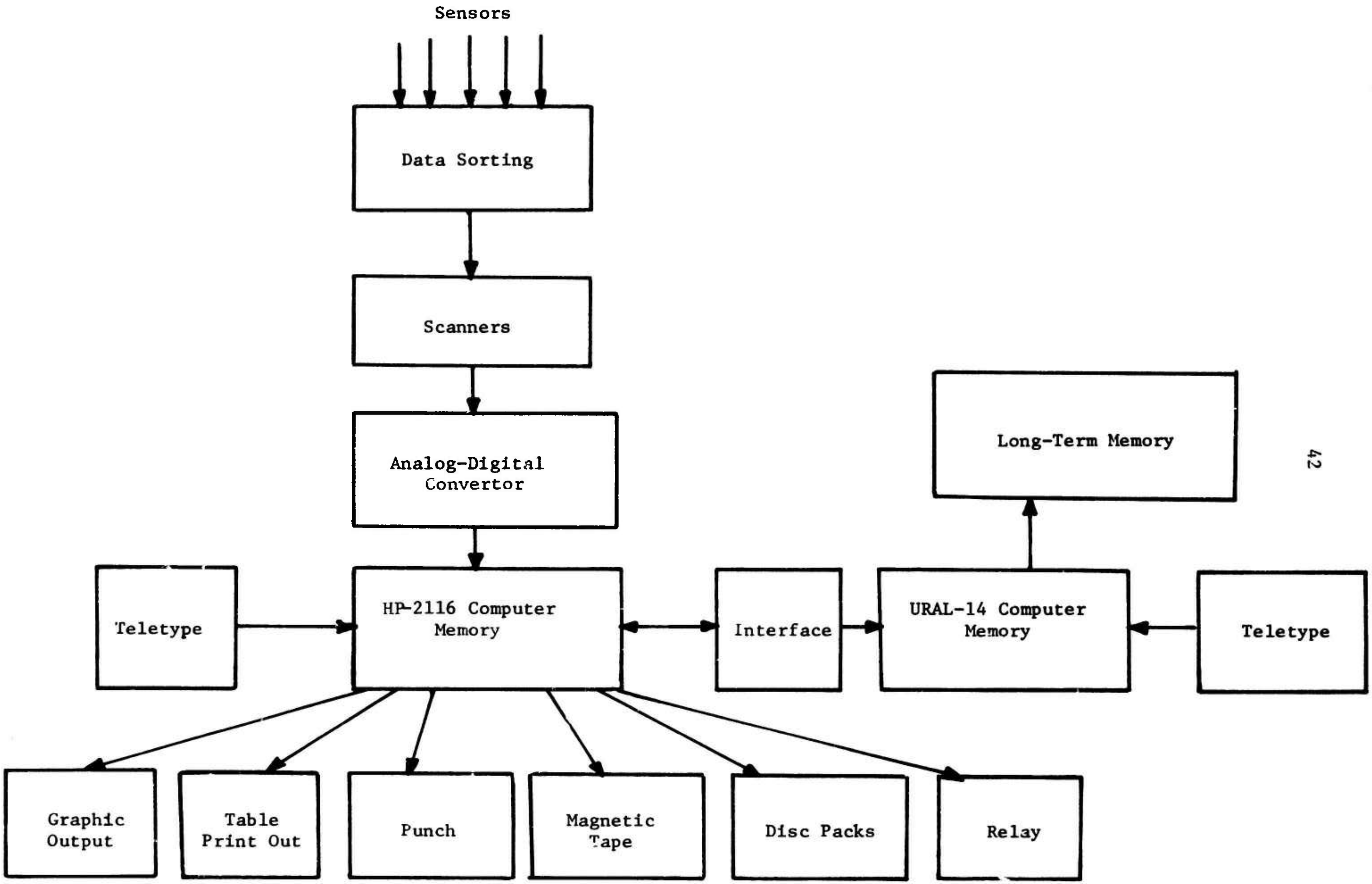


Fig. 12 -- U-25 sensing and data processing system [28]

Fig. 13 -- Ural-14 computer center for the collection and processing of F-25 data [28]

appears to be similar to that of a teletype. In a country where even domestic first-generation computers are scarce (by U.S. standards) and U.S.-built computers are almost nonexistent, the exclusive use of a relatively recent Soviet model together with a U.S. machine is an indication of the high priority assigned to the project.

The Soviets do have faster, larger, and newer computers -- e.g., the BESM-6 and some of the Ryad line of machines -- but they are very few in number and the Ural-14--HP-2116 system appears to be more than adequate for the needs of the U-25 plant. Typical computer problem solving in MHD does not require high-speed processing as much as extensive information-storage (computer-memory) capabilities, particularly problems requiring the solution of Laplace's equation. The Ural-14, with its modest operating speed but relatively large core memory, seems to be tailor-made for the application [35]. Figure 14 shows the U-25 central control room.

Conservative figures for the Soviet generator design involve the use of rather low combustion-chamber pressure and a low magnetic field. This situation is somewhat improved by the use of an exhaust fan to drop the pressure through the rest of the system relative to that necessary for direct atmospheric discharge. Lack of experience with high-performance generators is especially evident in the selection of an unreasonably small number of electrode pairs for a segmented Faraday generator. The U-25 has only 48 electrode pairs, whereas U.S. studies have shown that a generator of that size would require a minimum of about 100 to limit the potential between adjacent electrodes to a maximum of about 40 v -- the estimated reasonable maximum value that can be sustained without suffering breakdown due to the axial Hall voltage. Figure 15 is a photograph showing the electrode arrangement in the actual channel. It is tempting to speculate that the number 48 was derived more from inverter practice than from MHD-generator-breakdown theory.

Knowledge of breakdown phenomena was generated in a number of U.S. laboratories in the early sixties and was a familiar topic of discussion in MHD-generator circles. This phenomenon was also observed in MHD accelerators. Although voltage drops as high as forty volts per segmentation were recorded by a number of U.S. investigators, thirty volts may be considered a more reasonable limit. The U.S. work on breakdown, in general, was never published because the breakdown phenomena is random

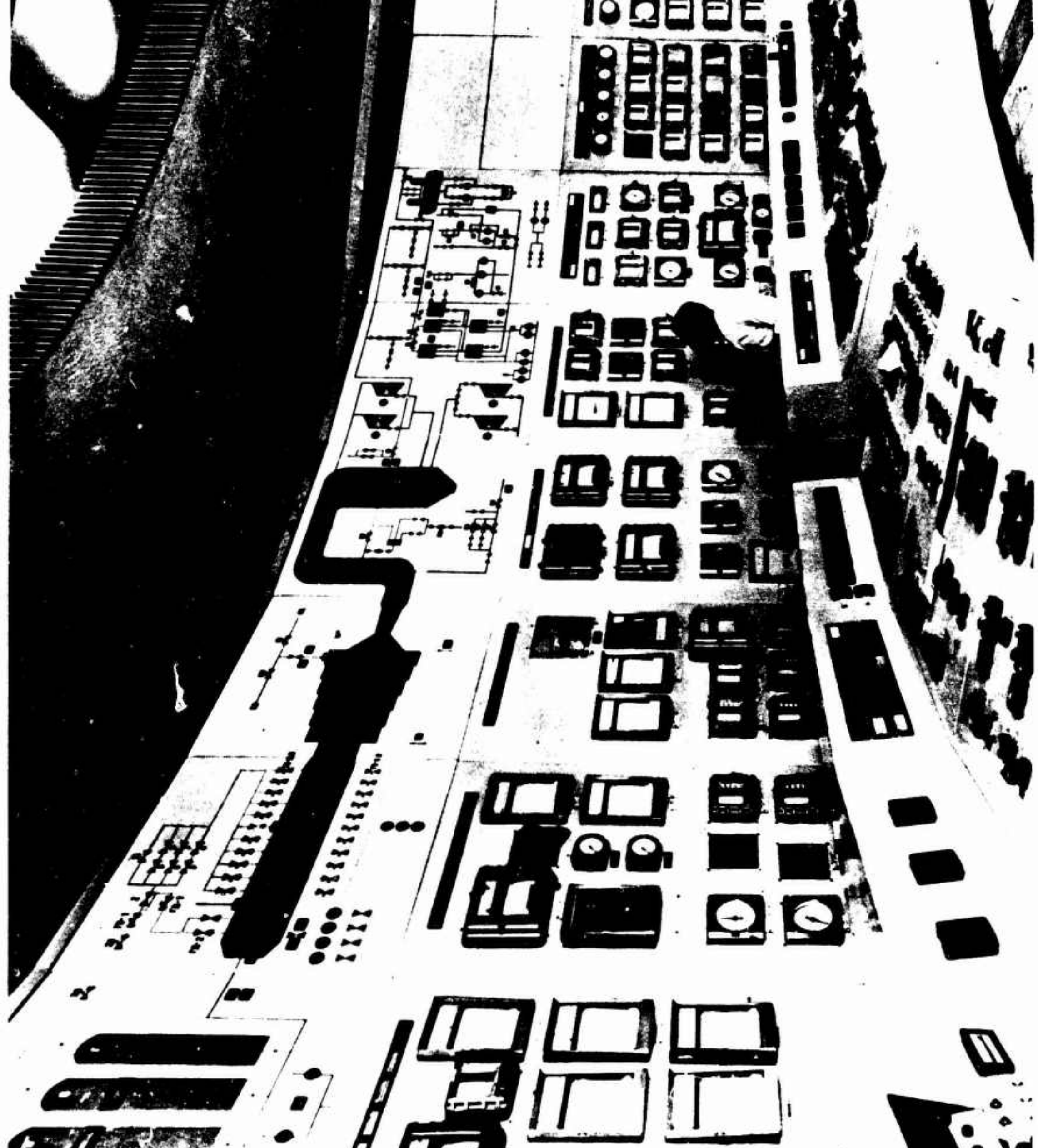

Fig. 14 -- U-25 central control room [28]

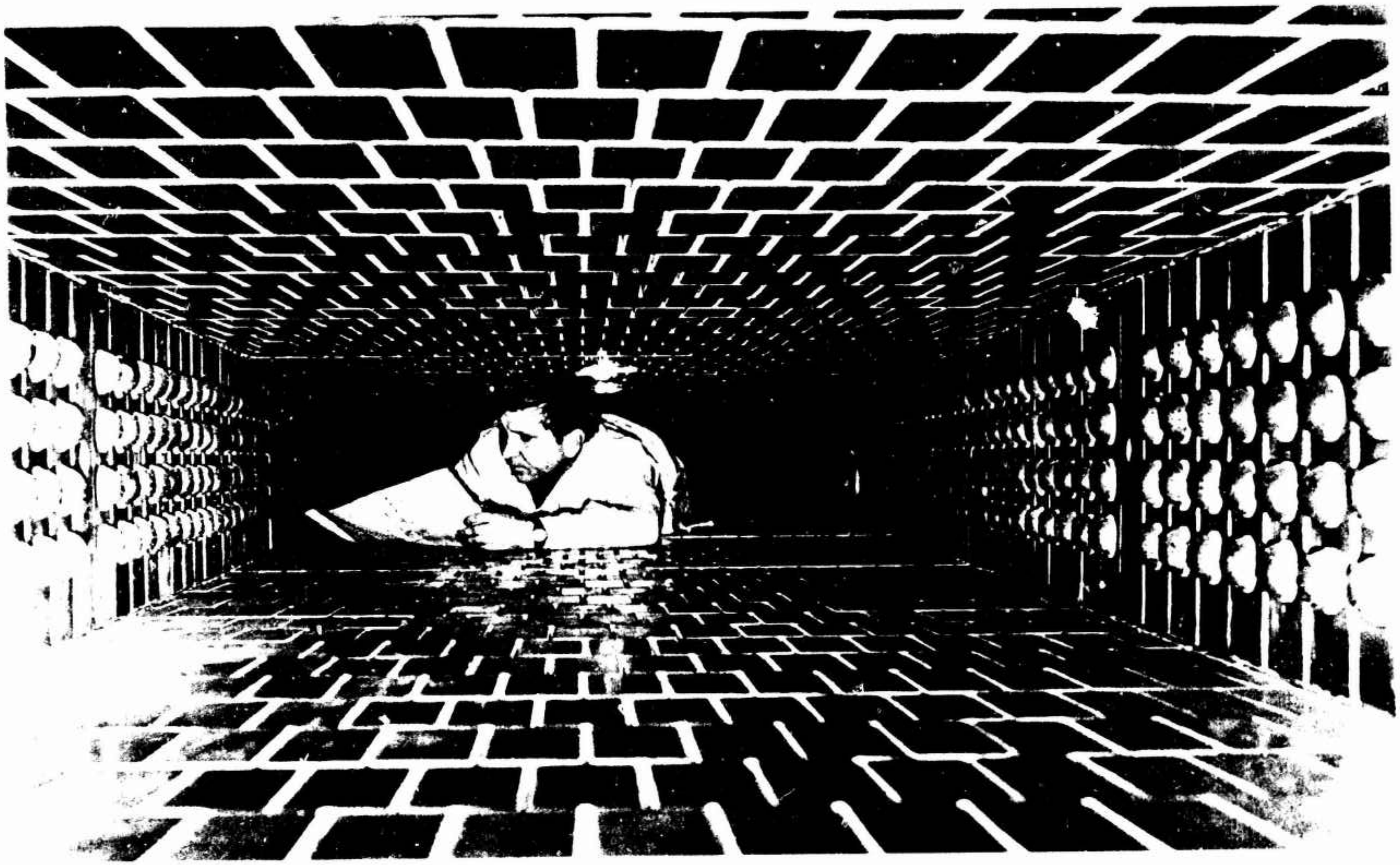

Fig. 15 -- Interior view of the U-25 MHD channel [23]

and difficult to study systematically. Thus, it is possible that the Soviets overlooked what was and still is common knowledge in the U.S.

Despite private Soviet denials, early U.S. visitors to the U-25 became convinced that the Soviets initially grounded both ends of the generator to short-circuit the Hall effect; this practice considerably limited the performance available under full design operating conditions. Although the Soviets later said that the grounding was deliberate, it was probably due to a lack of understanding and experience with high-performance generators. The problem arose from the fact that, according to theory, when the temperature of the plasma falls below 2300° K, the flow is nonconducting; but the mistake was to fail to estimate the breakdown potential of such a gas, which is quite low. During the initial visit to the U-25, it became obvious to the Soviet technicians that the Americans believed the generator to be shorted out. It was not stated at that time that this shorting had been done on purpose. As a matter of fact, shorting between the combustor and the boiler tubes is dangerous, because of the possibility of arc damage in both places. It was not until some four months later, at the Engineering Aspects of Magnetohydrodynamics meeting, when a side reference was made to the effect that the generator had been purposely shorted out. In an attempt to achieve the nominal output of about 25 MW within the field and combustor limitations imposed by the design, the Soviets introduced the concept of variable loading, and this is clearly brought out in their major published calculations of U-25 performance [28].

The Soviets privately outlined an ambitious three- to four-year program to develop the installation from the present large, simple, cold-wall generator arrangement to a progressively more advanced channel and combustors until maximum power can be obtained for several hundred hours. Little is known of the as yet uninstalled advanced channels in the U-25; hence, it is not possible to estimate how realistic the attainment of 25 MW in three to four years may be. It is to be expected in installations of this type that progress toward full power is made step by step. After about 18 months of U-25 operation, typical MHD operation is for an hour, with a peak power of 5 MW and sustained operation at a rather lower level. As mentioned earlier, calculations made in the U.S. have

shown that it will be exceedingly difficult to achieve 25 MW with the U-25 pilot and that 15 to 17 MW is a more likely ultimate value. With the present cold-wall channel operated under full flow conditions and with the other previously described limitations, a maximum of only 8 to 10 MW can be expected (according to both U.S. and Soviet calculations). The output of 5 MW attained by the U-25 can be considered to be about 50 percent of the design value. And, since this power was achieved with a reduced mass flow (40 kg/sec instead of the design value of 50 kg/sec) and reduced combustor temperature (about 100° C lower than planned), the Soviet results closely correlate with the expected results derived from generator theory and indicate where improvements have to be made to achieve the anticipated performance.

At its present stage of development, the U-25 is limited more by the underperformance of the system than by the conservative design of the generator itself. Basic generator performance falls off rather sharply when the generator is operated off design conditions; the cited reduction of mass flow and temperature are probably the most important factors limiting performance at the present time. The limit of 10 MW is imposed basically by the channel design. The substitution of U.S.-type finely-segmented channel walls for those currently used would facilitate changing the loading so as to probably raise this power to 15 MW. The protruding electrodes of the U-25 increase friction but probably also increase output by about 1 MW (with the cold-wall design) over that attainable in a flush-mounted electrode arrangement. Overall, it appears that the U-25 is progressing slowly, but nevertheless progressing, towards its design objective of 1000 hours of operation in the 20-MW region.

The availability of such large facilities as the U-02 and the U-25 has also enabled the Soviets to conduct an extensive materials-testing program under actual MHD conditions, although they are limited by the low magnetic field employed and a corresponding low axial voltage. It is important to emphasize that, especially in the MHD generator duct, it is the electrical conditions which dominate in the deleterious effect on materials and that only in an MHD environment can materials be evaluated realistically. The ability of the U-25 to achieve this is clear, in that the mass flow, axial field strength, and electrode current densities are appropriate to baseload conditions. On the other hand,

the U-02 is perhaps a factor of five too small to ensure that electrical conditions, particularly arc breakdown, can be properly established. Thus, the very extensive materials testing undertaken by the Soviets must be subjected to a further round of evaluation under realistic baseload conditions.

An approach more akin to that of U.S. investigators is to be found at the Krzhizhanovskiy Power Institute, where the MHD group has set up the ENIN-2 natural-gas-fired test facility. Pure oxygen is used as the oxidizer, and the total mass flow is about 15 kg per second. The typical run-time is a few minutes, the limitation being set by the magnet, which is not water-cooled for continuous operation -- a feature that is now being changed [36, 37]. The channel in this facility uses more advanced MHD generator approaches than those used in the U-02; however, U.S. specialists judged the materials employed as not the best for MHD conditions. For example, the ENIN-2 group used cold electrodes made mainly of brass, although another section of their Institute demonstrated the poor performance of brass in basic electrode studies. The various groups employing the cold-electrode approach found copper to be much superior to brass, and copper was used in both the U-02 and the U-25. The ENIN-2 performance has been rather poor: Power levels of around 1 MW are the best that have been achieved. In a facility of this size, using pure oxygen, a power output of around 10 MW should be attained. The most likely explanation for this situation is that the generator, although operated supersonically at Mach 2 or 3, is choking due to an insufficient divergence angle. This must be taken as conjecture, as no U.S. calculations have yet been done on the ENIN-2 and the Soviets have not indicated encountering this problem. Figures 16 and 17 are schematic views of this facility. Figure 18 is a schematic of a superconducting magnet which, according to private Soviet sources, is under development for the ENIN-2.

Little is known about the fourth open-cycle installation in the USSR, which is located in Kiev and operated by the Institute of Electrodynamics of the Academy of Sciences, Ukrainian SSR. The Kiev facility utilizes an old power plant that can be operated either with the MHD exhausting directly to the atmosphere or through a bottoming steam plant. Figures 19 and 20 show the layout of the plant. Like the U-02, the Kiev facility

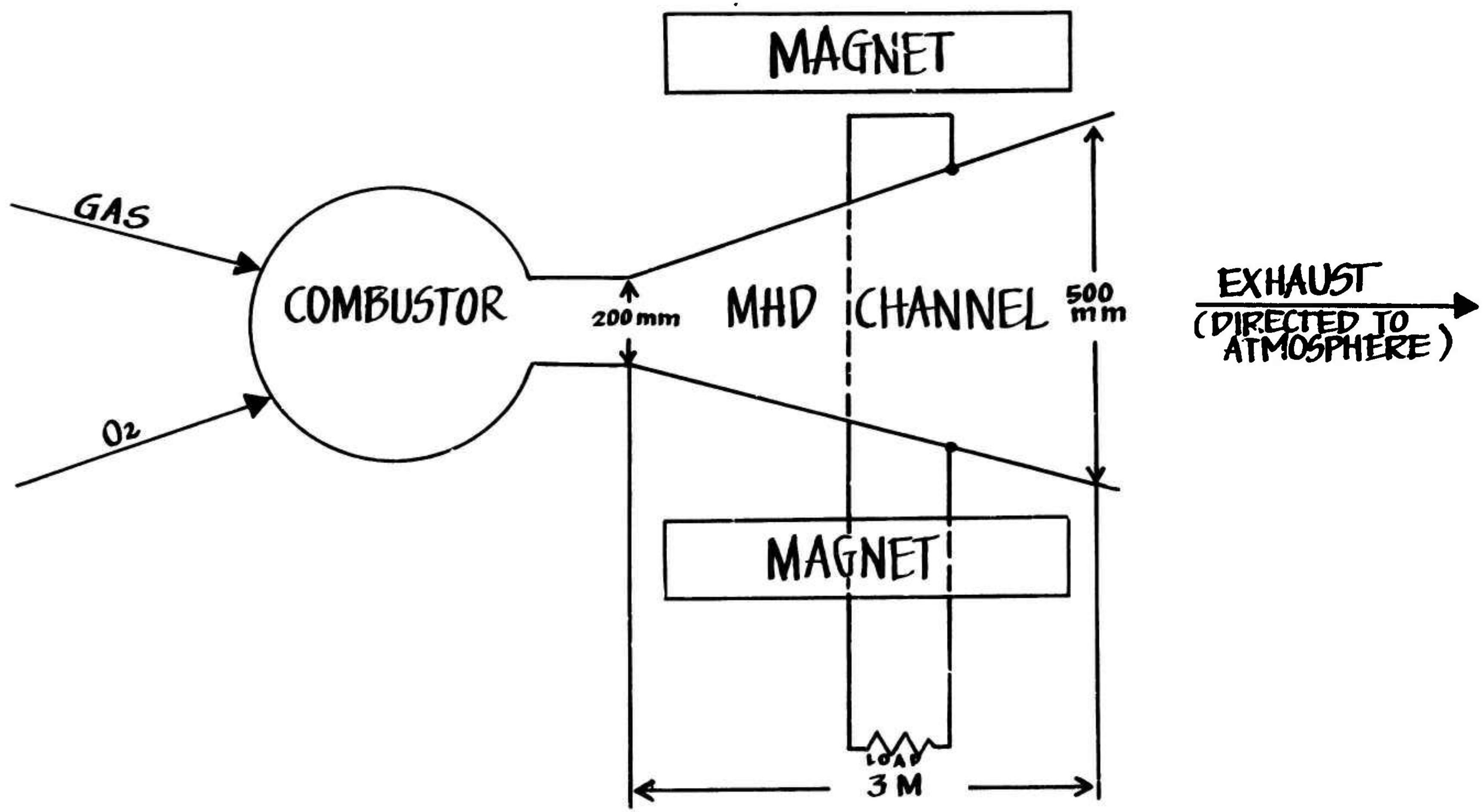


Fig. 16 -- Schematic of the ENIN-2

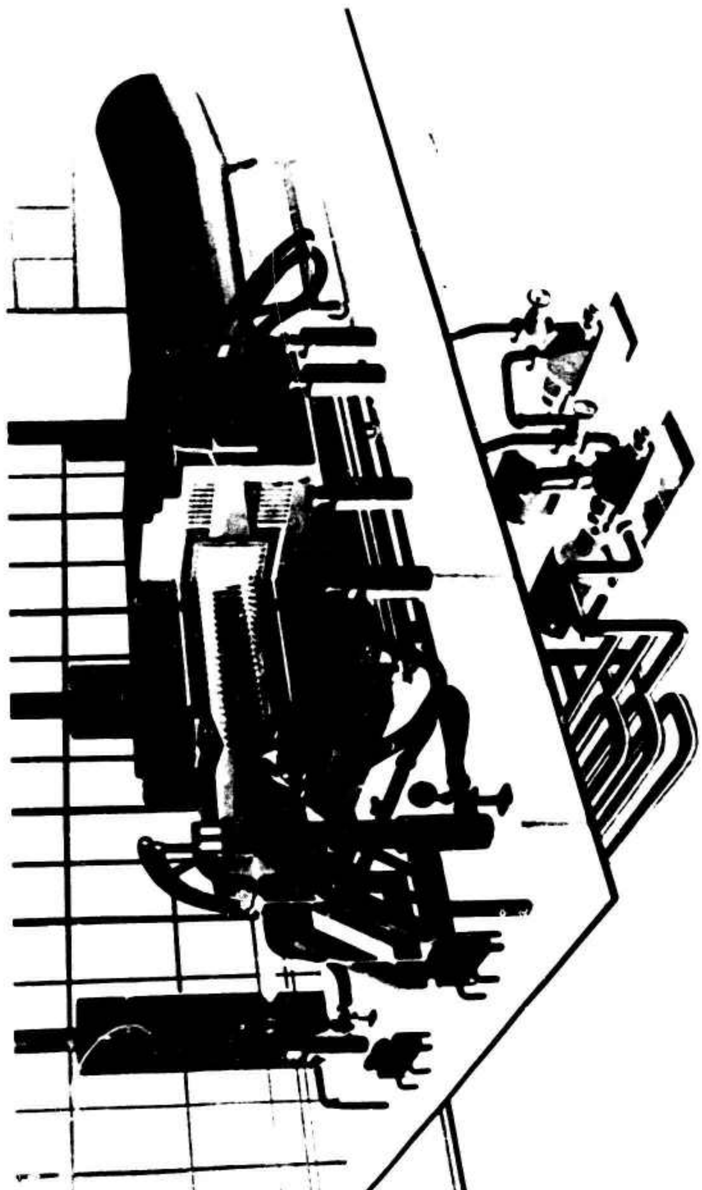

Fig. 17 -- ENIN-2

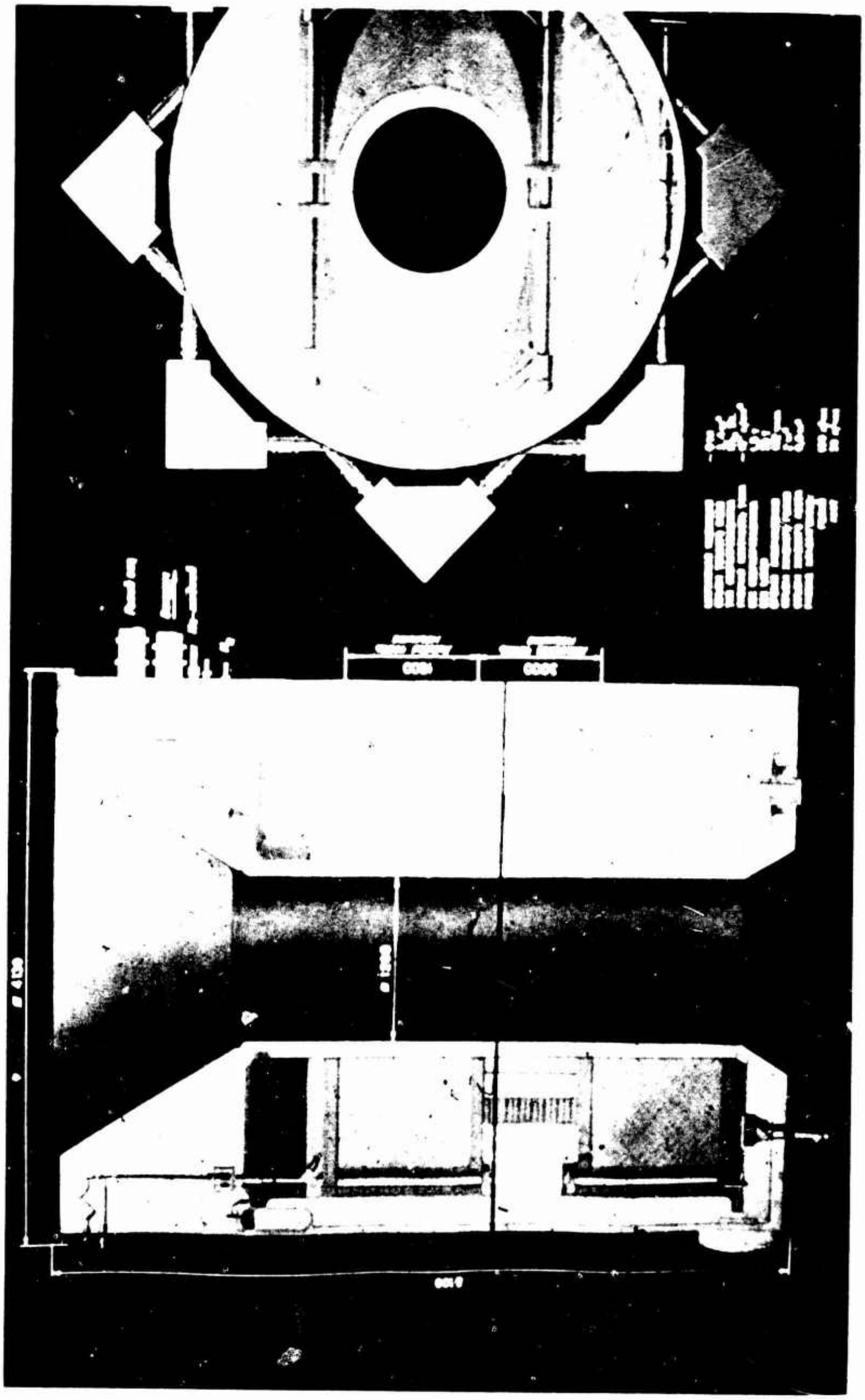

Fig. 18 -- Superconducting magnet system proposed for the ENIN-2

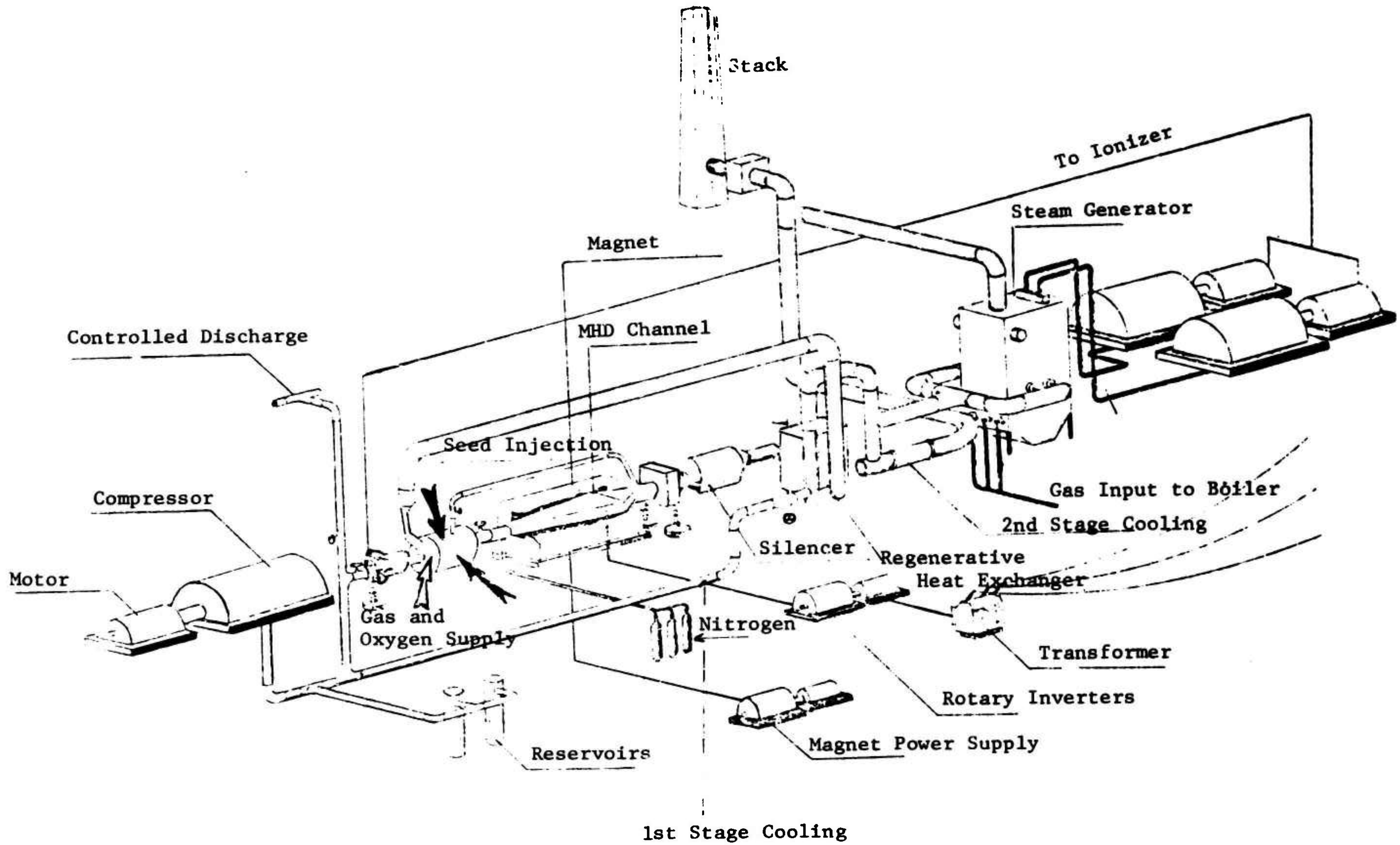


Fig. 19 -- Kiev facility [38]

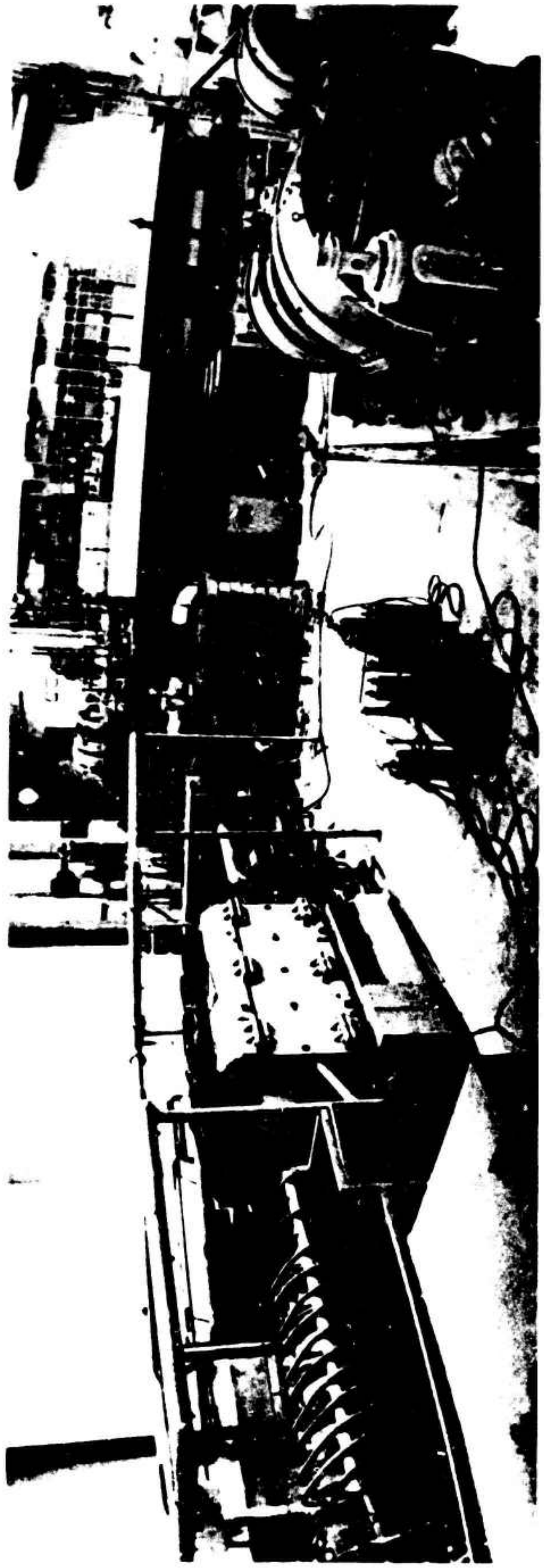

Fig. 20 -- Kiev facility

is a small power plant, fired by natural gas [38]. The mass flow is double the 2 kg per second of the U-02 [26], and again, the number of electrode pairs -- six [3] -- is grossly insufficient. Soviet sources have reported no experimental results, but have said that the Kiev plant is intended to deliver 8.35 MW(t) at 2850° K and Mach 0.7 [38]. A rough estimate of the axial field strength, based on a total Hall voltage under operating conditions of 1000 v, indicates that there should optimally be about 50 electrode pairs -- about the same number as is employed in the University of Tennessee generator, and again it may be that this group had only a limited number of electrical converters at its disposal.

Another open-cycle installation that has been mentioned by Soviet workers but not discussed in detail in the literature is the U-020. It is possible that the U-020 represented an effort to develop supersonic generators operating at higher pressures than in the U-02 and U-25 installations. If the U-020 is comparable to any U.S. installation, it would probably be to the early facilities operated by the University of Tennessee group, both at the Arnold Engineering Development Center and at the University, in that the mass flow was supposed to have been around 1 kg/sec and substantially supersonic conditions were achieved. Some Soviets have said privately that the U-020 failed destructively; in any event, news of it has not appeared for several years. At the Institute of High Temperatures, a prototype superconducting magnet was used with an explosively driven flow to demonstrate the compatibility of MHD power generation with superconductor technology (Fig. 21). Some information on the magnet is available in the literature, but it does not reveal anything new [39, 40].

Several U.S. organizations have worked on open-cycle MHD generators and, with one exception, have published essentially all their results in open literature. The Avco Corporation at its subsidiary, the Avco-Everett Research Laboratory, has been responsible for more than half of the U.S. MHD expenditure and by far the largest and most sustained U.S. effort. The only other industrial organization that has maintained a continued interest in open-cycle MHD is the Westinghouse Research Laboratory. Its only test facility has not been operated since 1963, but it is being rebuilt at the present time and is expected to go into operation shortly. In the early 1960s, the General Electric Company

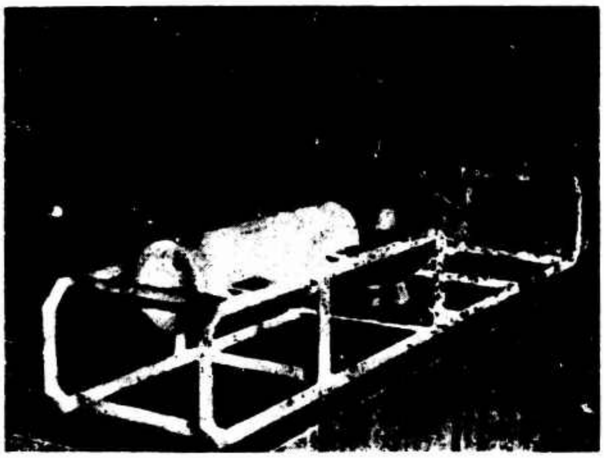

Fig. 21 -- Prototype of explosive MHD generator [39]

operated a simulation of a combustion-driven test facility, but this facility was closed and dismantled when GE decided in 1963 to end work on MHD. Reynolds Metals is known to have conducted a fairly lengthy MHD program but has always maintained company secrecy with regard to the nature of the installation and results obtained. It is not known if this is still in operation.

The remaining facilities are at universities and government laboratories. Of the university facilities, those at the University of Tennessee's Space Institute in Tullahoma [41] have the longest record of continuous operation and have yielded the most detailed study of MHD generator performance made anywhere in the world. At Stanford University, an open-cycle facility has been used to study basic plasma physics, electrode phenomena, and fluid mechanical effects, but not to study the performance of MHD generators themselves [42]. The Arnold Engineering Development Center (AEDC), also in Tullahoma, Tennessee, built and operated a number of facilities of which the LORHO, designed and constructed by Avco, is the best known. The Aero Propulsion Laboratory at Wright-Patterson Air Force Base, Ohio, has an in-house facility for testing small, high-performance generators.

At Avco, a team of MHD researchers under the leadership of Arthur Kantrowitz made major contributions to the understanding of generator operation. The Avco Mark I, an arc-heated, argon-seeded flow was designed only to demonstrate the scientific feasibility of MHD. With the Mark II,

a 2-MW electrical facility that operated for about ten seconds, a great de of fluid mechanical data was obtained for the Avco-AEP Electric Ut ty Program described in the previous section. The Mark IV [43] was a long-duration facility utilized for materials testing. The Mark V was a large multimegawatt-output machine intended to demonstrate the capability of rapid startup with MHD generators; it was never used for generator development.

Little information is available on the Mark V, or on the LORHO at AEDC probably because of their poor performance. Both can be considered "mature" generators, but their construction and operation performance were the results of overly ambitious projects for which the proper technical groundwork had not been laid. They have the value of showing that it is possible to extract large amounts of power from a large machine, but because of the way they were operated and because of the lack of publications concerning them, they did very little to advance the state of MHD generator art.

The thermal input power of the Mark V and LORHO was in the 400- to 500-MW range, and respective output powers of 32 and 18 MW were obtained for a few seconds. The power producing runs, including startup, for both installations were of a total duration of about 90 seconds, with the operating conditions being adjusted to establish a steady flow over the initial 10 to 30 seconds. It should be emphasized that these machines were designed to meet specific output conditions; they were not designed for maximum enthalpy extraction. The Mark V, a continous-electrode Faraday generator, was operated at a relatively high magnetic field. It suffered from being a self-excited generator and, thus, difficult to operate. Such a complex system was very optimistic at that stage of MHD development. Fortunately, the advent of superconducting magnets makes any repetition of this design unnecessary. The LORHO, a Hall generator, was operated at a relatively low magnetic field. The published results indicate that the LORHO was unable to maintain its rated power output, presumably because the Hall channel had been selected for the two-terminal output required by the LORHO specification. The Hall generator was known theoretically to be a poor choice for power extraction in the combustion-driven MHD regime and proved to be even worse than predicted by theory. Extensive attempts were made to get the LORHO to perform; its eventual

peak performance was 18 MW, followed by an immediate falloff. This was achieved under combustion conditions far different from those used in the original design calculations.

In terms of gross electrical-output power, the measured performances of the Mark V and the LORHO exceeded that which the Soviet U-25 is likely to achieve, but the operating conditions of the Mark V and LORHO differed considerably from those characteristic of the U-25 baseload operating conditions. Unpublished U.S. calculations suggest that the U-25 is more nearly a "U-15" -- that is, an installation limited to a 15-MW (rather than 25-MW) maximum output -- because of its performance-diminishing combination of a low combustor pressure (less than 3 atmospheres), low magnetic field (2 Tesla), and relatively low oxidizer preheat. These conditions make it exceedingly unlikely that the U-25 installation, at least in its present form, can equal the performance of U.S. generators built ten years ago under admittedly rather different operating requirements. The U-25, however, has the capability of sustained long-duration operation.

The Mark V and LORHO were followed, however, by a series of careful experiments on MHD generators in which problems associated with the large machines were systematically solved, resulting in increased understanding. It is on this basis that the current U.S. central power effort is going forward -- i.e., with the groundwork properly laid for future development. [8] The Soviet program is something like the Mark V and the LORHO programs in that insufficient work was done on the generator before the facility was constructed. However, the Soviet effort is different in one respect. It is going forward, the generator is being run carefully; data are being generated: and the next generation of generator channels is already planned for installation. In the two cited U.S. military generators, the Air Force altered its views on objectives and switched to another development area instead of trying to correct the difficulties.

The Avco Mark VI, completed in 1972, was the first long duration MHD facility large enough to simulate all the conditions, especially arc breakdown, found in large generators. The Avco Mark VII is essentially a rebuild of the old Mark II facility, with a water-cooled magnet. The Mark VIII is a large shock-tube facility intended to simulate large combustion-driven generators using the disc as opposed to linear geometry.

At the present time, the available operating facilities in the United States are the Avco Mark VI, VII, and VIII, the University of Tennessee Space Institute facility now upgraded for long-duration operation and capable of being fired with coal, the Stanford University facility, and the high performance test facility at the Wright-Patterson Air Force Base. Westinghouse, as already mentioned, is constructing a new facility, and the LORHO was reactivated recently for generator testing. Hercules is also constructing a high performance generator test facility for special applications.

The six U.S. facilities currently available, together with the two under construction and the reactivated LORHO, provide great flexibility for the study of MHD generators under various conditions appropriate to both baseload and special applications. Only one Soviet installation, the ENIN-2, has the flexibility associated with all of the cited U.S. installations which enable MHD generators to be developed on an engineering basis. Of particular importance is the long duration capability of the Avco Mark VI and the University of Tennessee installations, both of which have the capability of testing MHD materials under conditions which represent a real MHD environment.

CLOSED-CYCLE PLASMA

Closed-cycle plasma MHD in the United States had at one time involved experimental facilities at MIT, Stanford, the University of Maryland, the University of Florida, the Avco-Everett Research Laboratory, and the NASA Lewis Laboratory, but only the Space Sciences Laboratory of the General Electric Company still has ongoing facilities. The General Electric facility is of the linear shock-tube type and thus operates for less than a millisecond, using mixtures of seeded and unseeded noble gases [44, 45]. Now in the process of being converted to a blowdown* arrangement, it has been used extensively and productively to study the performance of closed-cycle generators operating in the nonequilibrium mode. The GE facility is the only closed-cycle MHD generator facility that has exceeded the highest enthalpy extraction

*A blowdown facility involves charging a heater either thermally or electrically and then driving a gas through the heated bed until the temperature has fallen to a minimum accepted value. Blowdown facilities extend operation from less than a millisecond in shock tubes to around a few seconds and are particularly well suited for inert gases which do not clog or damage the heater bed or elements.

obtained in the largest open-cycle MHD generators. Power levels of up to 1.2 MW at enthalpy extractions of up to 13 percent and thermal power of 10 MW have been achieved at temperatures as low as 3100° F. The NASA Lewis facility (work on which was recently discontinued) was basically of the closed-loop type and the gas (cesium-seeded argon) was electrically heated with a thermal power of 1.5 MW.

The major Soviet effort in closed-cycle plasma MHD has been conducted by a group under the direction of E. P. Velikhov at the Kurchatov Institute of Atomic Energy, primarily at experimental facilities in Krasnaya Pakhra, some forty kilometers outside Moscow. The facilities include: a large linear shock tube, similar to one at General Electric; a blowdown facility, the Kurch-I, with a 150-μsec test time and a thermal power of 100 kW [46]; a Faraday-type closed-loop Ar-Cs facility, the Kurch-II with heated walls [47]; and a rig for testing the properties of cesium above the critical point [3].

According to the open literature, these installations appear to be directed toward basic investigations in generator phenomena, but they have been the subject of considerable speculation in the United States. Collectively, they represent an effort about equivalent to the several U.S. groups mentioned earlier and appear to have gone through the same sequence of program development. In the early stages, there was concentration on the phenomena associated with non-equilibrium ionization, which is commonly utilized in closed-cycle systems. Velikhov, as a pioneer in the instability field, conducted a number of elegant experiments [46, 48-50] to demonstrate the associated plasma instabilities and to study their effects from the plasma-MHD viewpoint. Parallel with this quite basic work, system evaluations were made for closed-cycle MHD, and the status of reactor technology was reviewed [51, 52].

The original motivation for designing two of the Soviet facilities mentioned earlier -- the blowdown facility, which is being used to study ionization instabilities, and the supercritical cesium rig for determining cesium's thermal and electrical properties at very high pressures and temperatures -- was undoubtedly to search for energy-conversion systems compatible with ultra-high-temperature fission reactors. As it became apparent that the required reactor was not immediately available (nor was it likely to be developed without

massive costs) and that such a nuclear-MHD system offered an uncertain potential relative to the liquid-metal fast breeder reactor, work at the Kurchatov Institute was apparently redirected toward basic studies of possible conversion systems for fusion reactors. Or, based on Velikhov's known interests, fusion energy conversion systems could have been the goal of the Kurchatov effort from its inception. The Soviet closed-cycle work, however, is not known to have reached the power-production stage achieved in the United States at GE. We deduce, from their open literature, that the extensive Soviet preoccupation with plasma instabilities led them to believe that the closed-cycle generator would never operate efficiently, and that therefore the effort was deemphasized.

Some closed-cycle work has also been reported by the Institute of High Temperatures, and visitors have described an arc-heated argon-potassium facility located in the basement below the U-02. The installation has been referred to as the Start facility [53-56] and has served as a preliminary test bed for materials for the U-02 [57, 58], in addition to its usual function as an experimental facility for closed-cycle studies. A small electric-discharge shock tube has also been reported [59] with an initial pressure range of 0.5 mm Hg and a Mach-number range of 6 to 13. The properties of mercury vapor [3], $UF_6$ [60], inert gases [5, 61], and other substances as MHD working fluids have been studied in the USSR, but have not yet led to any significant developments.

Other, secondary, facilities are scattered around a number of other institutions, including a small subsonically-operated non-equilibrium MHD generator consisting of a 140 mm quartz tube with a 7-mm internal diameter and three pairs of tantalum electrodes which has been reported at the Institute of Radiophysics and Electronics in Kiev [62]. They, however, appear to have very little impact on the Soviet program as a whole.

Closed-cycle plasma MHD, unlike open-cycle, currently appears to be at a very low level in the United States and USSR (the GE program, for example, employs only five senior professionals plus supporting staff in four closed-cycle MHD programs) and appears to face a rather uncertain future in both countries. The concept of closed-cycle MHD

driven by a nuclear heat source is limited in both countries by the nonavailability of a suitable reactor, and there is no evidence in the public realm to indicate that MHD reactor development is being stressed in the Soviet Union. The most sophisticated experimental work in this field has been undertaken in Italy at the Frascati Research Center [63] and, in terms of experimental generator development, both U.S. and USSR work appear to have taken second place to the Italian effort (although GE would dispute this view). The United States (GE), however, has achieved the highest reported enthalpy extraction. The Soviets contributed the first basic studies of the ionization instabilities peculiar to nonequilibrium ionization [48] and computer-simulated [49] investigations. In terms of understanding the performance of nonequilibrium generators, the work at General Electric is especially sophisticated [44, 45] and does not appear to have any counterpart in the USSR -- although the Soviets may have intended to use the shock tube at the Kurchatov Institute for this purpose. Soviet researchers, however, claim that the shock tube was designed for extremely high pressure application, and not for conventional closed-cycle MHD. Experts in both countries tend to agree that, except for basic studies, this area of MHD is not particularly profitable to pursue at the present time. In the U.S., however, the GE group has made a case for using nonequilibrium closed-cycle systems with fossil-fired heat sources [9] which is attracting increased attention. They firmly believe that the latter approach has as bright a future for central-station application as open-cycle MHD. Soviet reactions to this proposal have not been forthcoming, but it is known that Soviet researchers did visit a French installation at Lyons which at one time was investigating fossil-fired closed-cycle MHD.

## CLOSED-CYCLE LIQUID-METAL

Experimental work on liquid-metal MHD began in the 1920s and thus predates that on the plasma systems. However, this work was concerned either with basic magnetic-fluid mechanics or devices where the conversion was from the mechanical energy of a fluid to electrical form (MHD flow meter), or vice versa (MHD pumps). Early liquid-metal-MHD-power-generation schemes involve two separate stages, the first being the conversion of heat energy to mechanical form and the second, the conversion of mechanical energy to electrical. In this context, the

liquid-metal MHD generator is an "electromagnetic water wheel," and the thermodynamics aspects of the overall conversion cycle are elsewhere. Most early liquid-metal MHD schemes involved the acceleration of a liquid jet or liquid droplets by the vapor of the liquid chosen and, after separation, passing the liquid through an MHD generator (the condensing injector and nozzle separator cycles). From the MHD viewpoint, ie liquid metal gave the feasibility of generating AC current directly (due to the high magnetic Reynolds number attainable), though the electrical efficiency was at least no better than in a plasma generator. However, this type of liquid acceleration is thermodynamically irreversible, and the overall thermal efficiency is accordingly low, typically from 3 to 7 percent, depending on the system. Thus, liquid metal MHD gained a reputation for low thermal efficiency and was assumed to be limited to special applications, such as space power, where such low efficiencies could be tolerated for overall system reasons.

The concept of a compressible two-phase flow expanding through an MHD generator enabled liquid-metal systems to perform in the manner of conventional heat engines, and as a result, overall thermal efficiencies rose drastically (up to 50 percent). First proposed in 1958 by P. Aigrain in some unpublished lectures at MIT, the two-phase scheme relied on the liquid metal to provide electrical conductivity, and used a gas, such as argon, to provide the thermodynamic working substance. Active U.S. work in this field dates from about 1963, when Petrick at the Argonne National Laboratory (ANL) realized that this was the most profitable way to pursue liquid-metal MHD [64]. It is clear that his work greatly influenced the increased Soviet interest observed since 1968 [65]. The two-stage aspect of early liquid-metal MHD schemes showed that preliminary experiments could be conducted on a simulation basis, using steam and water or a sodium-potassium alloy and nitrogen, and several small facilities using these fluids were constructed and operated.

Emphasis in the Soviet programs at the outset appeared to be centered on the condensing injector and separator cycles [66, 67]. An early paper on two-phase-flow conductivity, however, suggests that there was also interest in the two-phase-flow-generator concept [68]. The Soviet programs progressed rapidly from basic studies and component development on simulated systems to complete power loops.

There have been notable accomplishments in the Soviet effort. Extensive studies were made of various cycles and component development. Originally, the one-component condensing cycles were emphasized [69]; subsequently, the potentially more efficient cycles such as the two component and multistage cycles were investigated [70, 71], and, most recently, the two-phase-flow-generator cycle was studied [72, 73]. Extensive analytical and experimental studies were made on a variety of generator types, including the AC induction generator [74-78], the DC conduction generator [79-81], the jet generator [82], and the slug-flow generator [83]. Generators have been tested at temperatures up to 1600° F. A variety of analytical [84] and experimental studies on nozzle performance (a key component) have been carried out under simulated conditions [85, 86], and with liquid-metal flows [85]; similar studies have been reported on the condensing injector [87].

With the operation of complete power systems, the USSR demonstrated the self-circulation feature of liquid-metal MHD systems under actual operating conditions, as well as system operation and dynamic response characteristics. In addition, the Soviets have tested various types of conduction and induction liquid-metal MHD generators at high temperature (1600° F). The Krzhizhanovskiy Power Institute has a 40 percent-efficient Faraday generator with conducting walls, operating at 1600° F with potassium; reported initial overall system efficiencies reached on the high-temperature small-scale power systems range from 1 to 1-1/2 percent [88]. It is believed that higher performance levels -- perhaps 3 to 5 percent -- have been achieved on the basis of recent advances in condensing injectors [89]. But the generally low performance seems to have caused some indecision with regard to proceeding with the building of the planned next generation of large multimegawatt condensing injector systems. This indecision appears to coincide with increasing Soviet interest, since 1966, in the two-phase generator cycle approach being studied at the Argonne National Laboratory.

Work on the two-phase generator cycle is known to be under way at the Krzhizhanovskiy Power Institute and at the High Temperature Institute [73]. A substantial activity at the latter institution was acknowledged at the time of the Twelfth U.S. Symposium on the Engineering Aspects of MHD by attending Soviet scientists, who stated that the USSR is currently expanding its liquid-metal MHD program to include two-phase generator studies. They indicated that they were particularly interested

in these systems because of their hi. . projected thermal efficiencies. Their analysis of the two-phase liquid-metal MHD power cycle corroborates some of the findings of the analytical studies carried out over the past two and one-half years at ANL. They referred also to an experimental program on two-phase liquid-metal MHD generators and said that they hoped to present some results at future symposiums.

The Soviet program on liquid-metal MHD appears to be larger than the present abbreviated U.S. effort in regard to the number of institutions involved, funding, and manpower levels. None of the U.S. programs has progressed to the point of building complete small-scale power systems. U.S. efforts have tended to be concentrated on more basic studies of the various system components of $H_2O$, freon, and NaK-$N_2$ systems that simulate high-temperature operation.

There is, in fact, only one small liquid-metal program in progress in the United States at present: The Argonne National Laboratory is operating a large NaK-$N_2$ facility for the experimental investigation of both single- and two-phase AC- and DC-induction generators. The most advanced and longest duration program, including a 5-MW system under construction, was conducted at the Jet Propulsion Laboratory, but it was terminated this year. The objective of the JPL program was to develop a power system based on the separator-cycle concept. The only other U.S. programs on liquid-metal MHD of any consequence were the MIT effort and the potassium facility at Atomics International -- both terminated in the late 1960s -- to develop the condensing injector cycle.

The hydraulic components of liquid-metal MHD systems were tested extensively in the United States with water as the liquid and nitrogen or steam as the gas. The experiments showed that nozzles, separators, condensers, and diffusers could be operated successfully and that they had efficiencies generally in accord with theoretical predictions -- e.g., two-phase nozzles achieved 70 to 80 percent efficiency. Direct-current generators were tested with efficiencies up to 76 percent. A self-excited induction generator was operated and end-loss compensation demonstrated with an efficiency of 35 percent. References 90-97 provide detailed descriptions of U.S.-program results.

Three complete, similar small-scale liquid-metal MHD power systems based on the condensing injector cycle have been built and tested in the

Soviet Union to date, according to information disclosed in discussions with Soviet scientists during the past eight years. The existence of the first facility became known at the Warsaw MHD Conference in 1968, when Shelkov described a high-temperature liquid-metal loop that had been in operation at the Kurchatov Institute of Atomic Energy for "the past few years." The loop is schematically illustrated in Fig. 22 and can be considered a small-scale initial prototype of a space power system in that it has a specific heat input and electrical power output. It is a closed loop with an auxiliary pump used only for startup. The loop was described as constructed of stainless steel and capable of "continuous operation." The overall efficiency of the system is reported to be 1.5 to 1.6 percent, and the recirculating potassium flow is 2 kg/sec. It was indicated that efforts were being made to improve component performance and achieve an efficiency of 4 to 5 percent, an increase that could make the system acceptable for space-power application.

This was the first complete liquid-metal MHD system in operation at high temperature. A great deal of preliminary research and development appears to have been carried out before building the hot loop; this suggests that work on liquid-metal MHD had probably been in progress since about the early 1960s. The Soviets acknowledged that they had succeeded in "testing a number of different MHD generators."

The Kurchatov Institute built a large mercury-cesium loop, the M-30, at Akademgorodok, but it is reportedly no longer in operation. This loop (Fig. 23) actually operated its MHD generator using cesium-mercury vapor and, accordingly, did not really qualify as a liquid-metal system. The facility was designed to operate at temperatures up to 1200° C. In operation, a 35-atomic-percent cesium-mercury amalgam was boiled at 900° C. The vapor was then superheated to approximately 1200° C and passed through an MHD generator with a magnetic field of 4 Tesla. The vapor, in passing through the MHD generator, reached Mach 1.8. The liquid-metal-vapor velocity within the generator was approximately 360 ft/sec and the thermal power input about 30 kW. The overall cycle efficiency for the facility was calculated to be 6 to 8 percent; the actual measured efficiency was not revealed. The generator channel, a variable area design, was ceramic and had segmented electrodes [98].

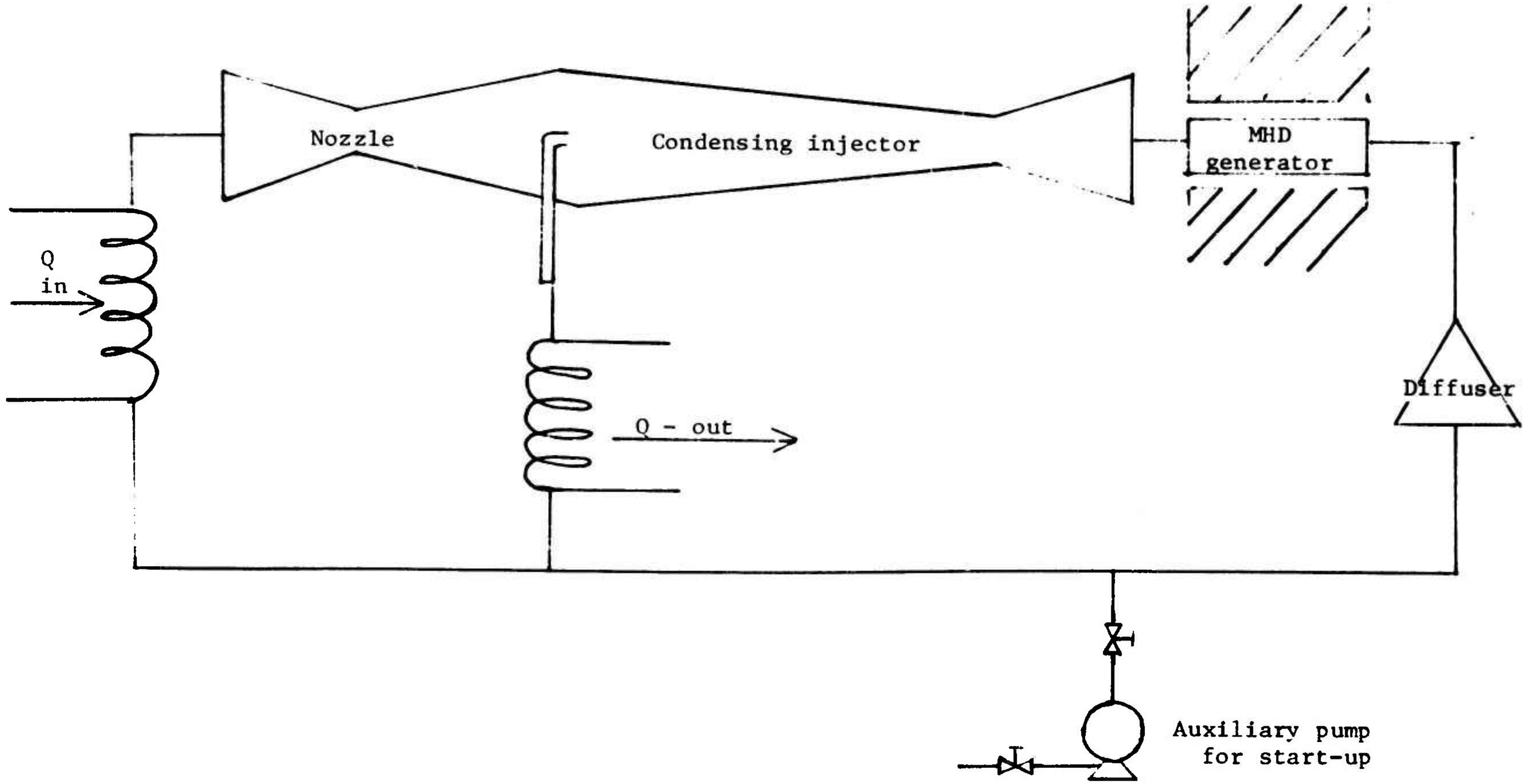


Fig. 22 -- Diagram of a small-scale high-temperature liquid-metal MHD test facility

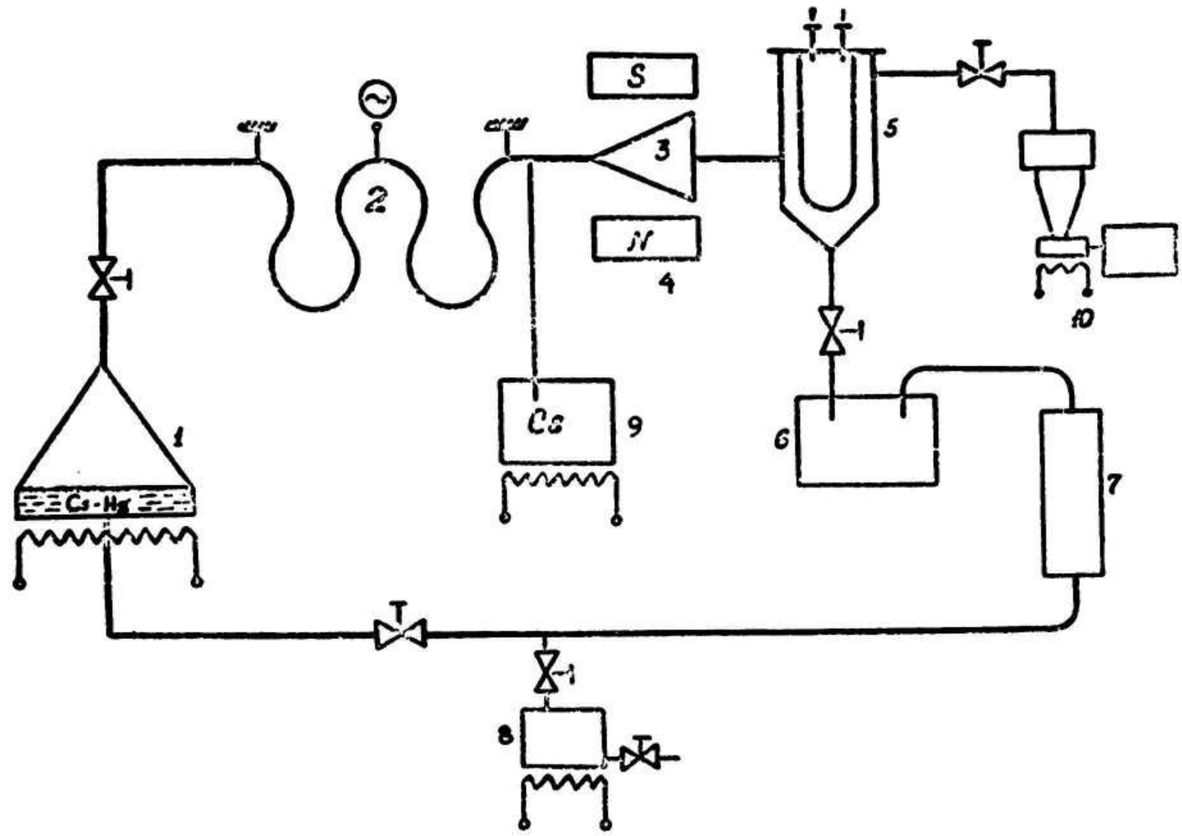


Fig. 23 -- M-30 facility [98]

1 - Cs-Hg (amalgam) vaporizer
2 - superheater
3 - MHD generator
4 - magnet
5 - condenser
6 - settling tank
7 - damper
8 - Cs-Hg reservoir
9 - cesium vaporizer
10 - mercury diffuser and other apparatus

The Krzhizhanovskiy Power Institute is operating a high-temperature potassium power loop which was built and put into operation in 1968. This facility has operated for about 1000 hours, 300 of which were at temperatures of 900° C. It was used to test the condensing injector with potassium at temperatures that would be used in an actual power cycle. The Soviets were successful in obtaining self-circulating operation with a condensing injector; in fact, they also tested a DC-MHD generator under these conditions. The net performance of the DC-MHD generator system was approximately 1-1/2 percent overall efficiency. The Soviets stressed to visitors that they were not interested in using this facility to demonstrate efficiency. The reported net power output from the potassium test facility was 1 to 2 kW. The basic objectives of the facility seemed to be a study of the dynamic response characteristics of the condensing injector MHD power system. Visitors who have seen the potassium facility were not impressed, and it has been disclosed that there have, in fact, been a number of operational difficulties, including leaks. The facility was described in [88].

Possibly the most advanced of the potassium condensing-injector power systems, according to Soviet sources, was put into operation several years ago at the Institute of High Temperatures. This system is reported to have a thermal-power input of 300 kW. The Soviets expect to achieve an overall efficiency of 2.5 to 4 percent with an advanced condensing injector as described previously. They have tested conduction and induction generators at temperatures to 1600° F and have indicated that they expected to achieve an overall generator efficiency approaching 60 percent. (This is a factor of about two higher than what has been achieved in the U.S. on cold systems.) Information on this facility is not available in the literature.

A group of Americans visiting the Krzhizhanovskiy Power Institute recently learned that a new facility of particular interest was built, namely, a 1-MW two-phase liquid-metal MHD system (see Fig. 24). The Soviets are considering running it at a maximum temperature of 300° to 350° C and a maximum pressure of 50 to 60 atm. with the working-fluid combinations being either $H_2O$ or $CO_2$ with tin (or gallium or indium). If this is done, the implication is that a light water reactor would be the planned heat source. The decision on which loop to construct was not made known. The gas (vapor) flow rate will

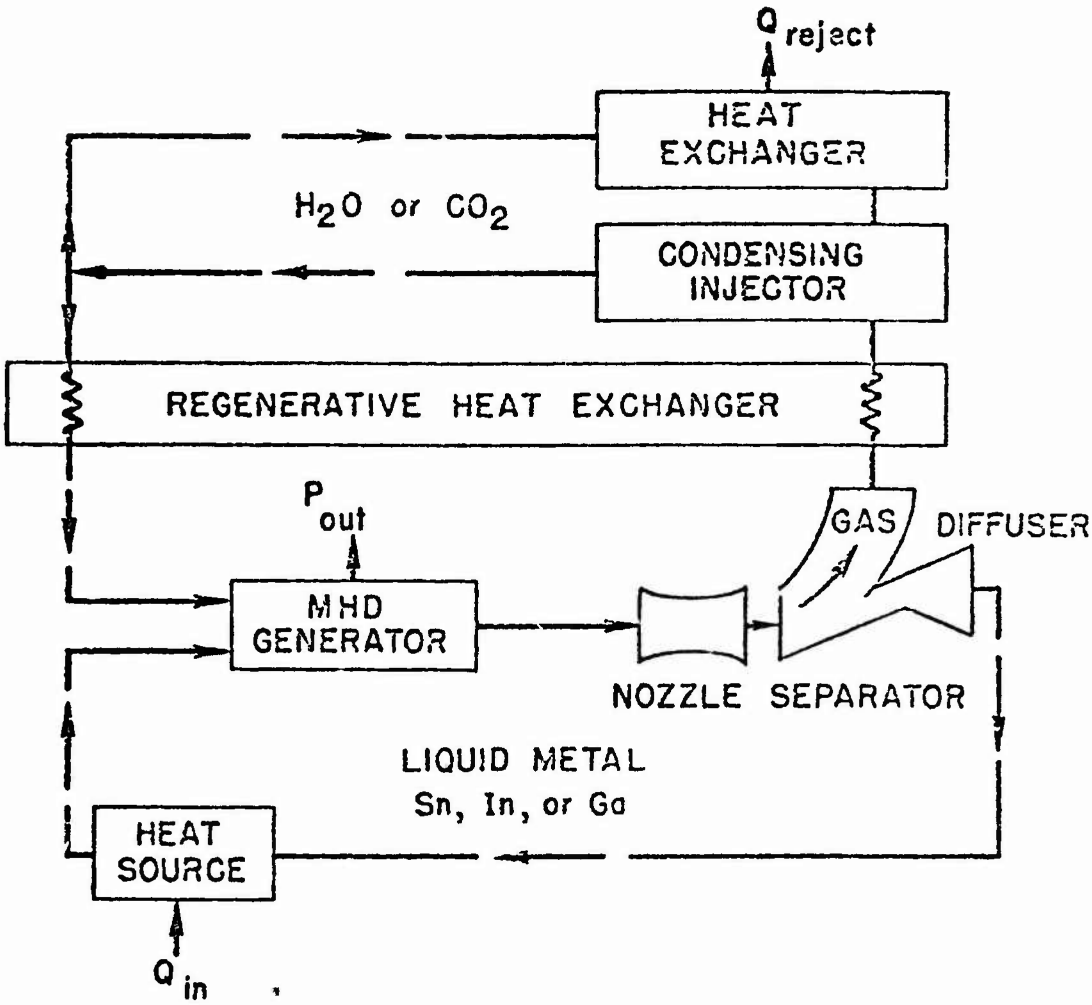


Fig. 24 -- One version of the 1-MW liquid-metal MHD system under consideration at the Krzhizhanovskiy Power Institute

be 2.1 kg/sec, with the liquid flow rate ranging from 21 to 210 kg/sec. The nominal design point appears to be a total flow rate of 50 kg/sec. The design power output will be 100 kW(e) (corresponding to an overall efficiency of 10 percent), the anticipated minimum output would be 50 kW(e). It was indicated that the two-phase MHD generator has been designed and is being built and that a small mockup of the power system has been operating for some time.

Sheindlin has taken the position that liquid-metal MHD must be still further evaluated before its true potential can be determined and has proposed that further research on injector-type systems (largely completed in 1968-1969) be divided into the following stages:

1. Continuation of theoretical and experimental work on the construction of effective injection mechanisms with the goal of, at least, gaining a theoretically well-founded estimate of their efficiencies.
2. Construction of a large-scale experimental liquid-metal MHD facility for the verification of simulation studies.
3. Further studies on improving AC liquid-metal MHD generators.
4. Evaluation of feasibility and potential applications.

## V. COMPARISON OF NATIONAL PROGRAM OBJECTIVES

High thermal efficiency in primarily baseload central-station power plants has continued to be the major goal in the commercial area, although emergency- and peaking-type installations have begun to receive increased attention. As the temperatures required for plasma MHD are not yet obtainable with nuclear reactors [99], interest in commercial plasma MHD has centered on fossil fuels. It is the highly efficient use of these fossil fuels provided by MHD generators that has become the justification for the development of MHD from the national energy resource viewpoint. There is a possibility that certain reactors (LMFBR and HTGR) currently under development could eventually be coupled to certain types of MHD generators (particularly liquid-metal systems).

The position of MHD differs in the major energy-producing countries. The European Economic Community countries, at least until recently, have been drifting away from coal for electric power generation, although resources are plentiful, if expensive, in Great Britain and Germany. The EEC countries have operated with fuel imports for many years and have long since adjusted their trading balance to make this a viable arrangement on the international money market. To the extent that any policy can be identified, the Western European nations have turned increasingly to oil for central-station power generation until nuclear reactors are available. Nuclear stations are expected to provide the baseload, while older, oil-fired plants cover the intermediate-range needs and gas turbines are utilized for peaking purposes. The EEC countries thus have an energy strategy which makes it difficult to justify MHD development, at least so long as MHD is linked to coal. The only scenario in which MHD might play a role using coal as the primary fuel is if a shortage of enriched uranium or oil developed or the balance of payments could no longer support the enormous cost of Middle Eastern oil. The availability of domestic coal, even at a high price, would then be a stimulant to MHD development because of the potential for high conversion efficiencies and low environmental pollution.

The possible scarcity of uranium appears to have been more appreciated by Soviet planners than by their Western counterparts,

who have assumed that the fast breeder reactor can be developed by the mid-1980s. On this timetable, the breeder could go into service on an increasing scale during the 1990s and, by the year 2000, handle a significant part of the total electrical energy demands of advanced countries. In addition, it could begin to supply process heat and electrical energy for synthetic fuel production, and so enable countries using this type of reactor to be increasingly less dependent on hydrocarbon fuels. The danger in this nuclear strategy is that the fast reactors may be delayed for technical reasons and that an increasing amount of uranium will then be required for light-water reactors. The difficulty will arise when cheap uranium is no longer available and it is necessary to turn to the much more expensive uranium in shale and rock.

Soviet energy planners have clearly relied less on light-water reactors than their Western counterparts and appear to be headed straight toward a fast-breeder-reactor nuclear economy. Indeed, the first demonstration plant of this type recently went into operation. These planners seem to contemplate the use of the vast reserves of natural gas and coal possessed by the Soviet Union for electrical power generation for many decades to come. There is a strong incentive, on the resource conservation basis alone, to develop more efficient plants than are possible with conventional technology. MHD has thus come to have a prominent place in the development of new energy conversion technology in the Soviet Union, and it enjoys high-level and continuing support. Deputy Premier Kirillin, who is also Chairman of the Committee for Science and Technology, has been personally identified with MHD development from the outset and has apparently attempted also to use MHD as an example of how Soviet scientific development can be taken to the applications stage.

Sheindlin's program at the Institute of High Temperatures is a major one, and in the twelve or thirteen years in which it has been in existence, the expenditures must have exceeded a quarter billion dollars (i.e., if the same work were to be done in the United States on the same scale). The activities at the Institute of High Temperatures appear to be coordinated with specialist groups in various laboratories

and universities around the country, thereby forming a more-or-less national program with several thousand scientists, engineers, technicians, designers, and other support personnel. In addition to the support of the Academy of Sciences, the program also has strong financial backing from the Ministry of Energetics and Electrification. Further, this Ministry, through the Krzhizhanovskiy Power Institute, maintains what has been described as its own in-house activities, notably the ENIN-2, apparently to have the means of independently pursuing the development and assessment of MHD.

Based on open literature analysis, all indications are that the Soviet open-cycle MHD program (which constitutes roughly 80 percent of their overall effort) is overwhelmingly directed toward commercial application, especially high-efficiency, baseload, gas-fired plants, but that peaking stations are also being considered. Work on nuclear-electric systems for both commercial and space applications was considerable at one time at the Kurchatov Institute but now appears to have been either terminated or deflected into basic investigations of conceptual schemes for energy conversion with fusion reactors.

In the United States, the interweaving of commercial and special applications MHD has been a feature throughout the development period since 1959. Organizations such as the Avco-Everett Research Laboratory have conducted most of their MHD development with support from both sources. A well-organized and purposeful commercial MHD program was conducted by Avco and the AEP utility group from 1960 to 1967. This carried MHD to the point where pilot plant construction was considered, but enthusiasm for nuclear power caused the cancellation of a proposal to build a 30-MW pilot plant. The desirability of having alternate strategies for energy conversion systems because of the long lead times involved in plant development became more apparent as delays in the fast-breeder-reactor program mount and existing systems encounter difficulties in adapting to environmental standards laid down by the Clean Air Act. Indeed, after 1975 most eastern coal will be virtually unusable as a conventional electric-power generating fuel because of the problems of meeting emission standards, particularly for sulfur dioxide. The urgent need to improve coal technology has been widely

recognized, although the tendency has been to emphasize gasification and liquefaction of coal rather than its use in other types of electric-power generation.

The plasma MHD central power plants compete well with the gas turbine, especially if they are directly coal fired. If a gasification plant is used in front of the MHD plant, however, the efficiency of both the MHD and the gas-turbine plants must be multiplied by the efficiency of the gasification plant; this would result in a low overall figure of approximately 41 percent for a first-generation system. Furthermore, the capital cost of a gasification plant must be added to that of the MHD plant. Thus, if gasification is used in conjunction with MHD, the total system cost increases and the total system efficiency decreases. It appears, however, that there is no need to incorporate a gasification cycle into an MHD power system, for U.S. experiments on direct coal-firing are progressing very well and are encouraging.

On his most recent visit to the United States, in July 1973, Sheindlin said that natural gas was too valuable for MHD use and that the Soviet Union must eventually use coal to power the plants. It appears that changes in the world market may, to a certain extent, have forced a change in Soviet policy. This would mean that the U-25 is headed in the wrong direction, inasmuch as gaseous fuel will be unavailable in the world for central power generation in future years. Sheindlin said that the USSR would have to run the U-25 for perhaps five years before it would be possible to reconstruct it or modify it for use with coal. He felt strongly that the way to acquire coal technology was to use natural gas first to learn how to use such plants and then to modify them for coal. Some noted U.S. MHD specialists believe just the opposite: that coal plants are totally different from natural-gas plants. Furthermore, the United States is not presently experiencing difficulties in gradually increasing the operation time of direct-coal-fired MHD channels.

Several studies of MHD and its potential for commercial service have been conducted since the demise of the Avco-AEP Utility Program. The first of these, prepared in 1969 by the Office of Science and

Technology [20], was instrumental in reestablishing interest in MHD in the United States. It recognized that MHD offered certain advantages for high-efficiency, coal-fired, baseload power generation, and recommended a modest research and development program to solve the key problems associated with coal firing. A $7-million-a-year program is currently under way through contracts from the Office of Coal Research of the Department of the Interior and the recently formed Electric Power Research Institute, successor to the Edison Electric Institute in utility research.

Considering separately the areas of nuclear space power systems, military applications, and pulse installation power supplies, some general trends can be discerned. The United States has decreased its efforts in the direction of deep space probes as a result of cuts in the overall space program and the difficulty of developing suitable ultrahigh temperature reactors for space power applications. The same factors may govern this situation in the Soviet Union. There is no known work currently in either country to utilize MHD specifically for space power systems.

The military area has until recently failed to produce a convincing application for MHD generators. Judging by the published literature, military influence is much more apparent in the United States than in the Soviet Union. In the early days of DoD support, exploratory research and development was the goal, but emphasis on MHD applications prevailed through the late 1960s.

U.S. systems design studies [97] have presented extensive data to support the feasibility of adapting the two-phase-flow liquid-metal generator cycle to submarine propulsion. Recent publications and discussions with Soviet workers indicate that there has been a reorientation in the USSR toward development of the two-phase-flow generator cycle. In his closing remarks at the 1971 Munich International Conference on the Engineering Aspects of MHD Power Generation, Sheindlin made the following statement:

> A great deal of attention has been given to the investigation of liquid-metal facilities with a two-phase-flow in the MHD generator. I would say that this was of specific interest at this conference and it is quite normal that a great deal of attention was, in fact, paid to it. Very interesting evaluations were made by Dr. Petrick in the U.S.A. and Professor Bidard in France. In our own country

> there were also some very interesting evaluations of this type, which have shown that the overall efficiency of such facilities should exceed 40 percent.... It should also be noted that apart from the calculated data, comprehensive experiments are being carried out on models and also on actual generators working with fluid mixtures. Specifically, we are studying the stability of such systems and the efficiencies and power densities that can be attained. All of this is not quite clear yet but we hold that this direction of research is of great interest.

The objective of the program to build a 1-MW power system based on a Rankine cycle variation of the two-phase-flow generator cycle at the Krzhizhanovskiy Power Institute, as described in the previous section, is especially interesting to speculate on. The choice of working fluids and the specific cycle configuration appears to stress compabitility with a water environment and elimination of rotating components. The cycle as shown in Fig. 24 (p. 70) utilizes a condensing injector to circulate the thermodynamic working fluid ($CO_2$ or $H_2O$) and a nozzle diffuser system to circulate the magnetohydrodynamic working fluid (Sn). The system could be utilized to provide electric power for submarine propulsion. It is interesting to note that an early paper [100] discussed a similar system operating with Sn and $CO_2$ but using the slug-flow generator, and discussed "low-temperature cycles for devices in which the condenser is cooled by cold water (as in ships, for example)."

The continuing programmatic efforts on the condensing injector and separator cycles, as evidenced by the operation of an advanced system at the Institute of High Temperatures for several years, is somewhat puzzling. It could simply be the end product of a long-range program that had developed substantial momentum. On the other hand, the objective of developing a power system for possible use in near space, although less likely, may still be a real one.

The use of MHD to power devices requiring large pulses of electric power for short times (typically a minute or less) has often been proposed. The most ambitious program to achieve this was conducted by the Institute for Plasma Physics at Garching (near Munich) in the Federal Republic of Germany and involved the development of a small generator to show the feasibility of powering the magnet systems of

pulsed accelerators. This may be a particularly appropriate application for MHD because of its unique capability to provide large bursts of power for short periods, but the first truly successful utilization of MHD for this purpose has yet to be made. Persuasive evidence suggests that the USSR is also looking at MHD as a power source for particle beams -- Sheindlin's MHD work at the Institute of High Temperatures was referred to as being very useful for particle-beam application [101], and it was said that the Soviet particle-beam specialist had been transferred to Sheindlin's Institute. However, the characteristics of an MHD generator that might be constructed as a particle-beam power supply are so different from those of the U-02 and U-25 (the major facilities with which Sheindlin is associated) that it is difficult to see the connection.

In September 1973, the Russian weekly, *Nedelya* [102], reported Soviet plans to use an open-cycle MHD generator in the Tien Shan mountain range. The generator will be used for continuous sampling of the effective resistivity of crustal rock under the Peter I ridge, for the purpose of earthquake prediction. Because of the remoteness of the region, the compactness and construction simplicity of the MHD generator (as compared with conventional turbine generators) is a great -- and perhaps the only -- advantage. *Pravda* later reported (February 8, 1974) that the generator had been developed by the Kurchatov Institute of Atomic Energy and that it was in the multimegawatt power range.

## VI. CONCLUDING REMARKS

The USSR has had a large, broad-spectrum MHD program for a number of years. Few aspects of MHD have been ignored, and the program has achieved some successes -- notably, the construction of a large-scale open-cycle MHD pilot plant, the U-25. Precise comparisons of U.S. and USSR dollar outlays are difficult; however, some U.S. MHD specialists and utility engineers have estimated the U-25 hardware cost to be on the order of $100 million. One American visitor cited a figure of $45-60 million [103], which appears to be somewhat low in terms of 1973 dollars. This is the cost required to construct similar hardware in the United States and, if accurate, would place the Soviet open-cycle program about five years ahead of that of the United States on a cost basis. Because of present cost limitations on the U.S. program, it is believed that the United States is about five years away from the construction of a plant of the U-25 type. And, judging from the large and ever-increasing number of Soviet published articles and the unconfirmed reports from private Soviet sources of large numbers of workers involved in the various MHD projects (one report claimed that 1000 workers were employed in the U-25 project alone [103]), the overall Soviet MHD effort is considerably larger than that of the United States and appears to be expanding. If the cost of the visible MHD facilities and the number of reported project participants is any indication of the relative efforts in the three MHD power-generation subfields reported in the Soviet open literature -- open-cycle, closed-cycle plasma, and closed-cycle liquid-metal -- the overwhelming bulk of the Soviet MHD effort is devoted to open-cycle studies.

A. E. Sheindlin, the Director of the Institute of High Temperatures in Moscow, stated unofficially that the USSR strongly favors pursuing all three areas of MHD power generation, but that the main thrust of their effort is in open-cycle MHD, which he estimated will take 20 to 25 years to complete, and consists essentially of four stages:

1. preliminary research
2. experience with the U-02

3. testing and evaluation of the U-25 facility
4. construction within three to five years of a 500- to 1000-MW(e) baseload MHD power plant (50 percent MHD and 50 percent steam turbine) using oil or gas fuel

Currently, the USSR has about a dozen known major MHD facilities. Five are open-cycle MHD installations -- the U-02 and U-25 at the Institute of High Temperatures, the ENIN-2 at the Krzhizhanovskiy Power Institute, the coal-burning facility at the Institute of Electrodynamics in Kiev, and the recently announced generator at the Kurchatov Institute of Atomic Energy (currently being used for earthquake prediction studies); four are closed-cycle plasma installations -- a large linear shock tube and two blowdown facilities at the Kurchatov Institute of Atomic Energy and an arc-heated argon facility at the Institute of High Temperatures; and two are closed-cycle liquid-metal installations -- a complete potassium loop at the Krzhizhanovskiy Power Institute and a reported loop at the Institute of High Temperatures.

Soviet closed-cycle research and related facilities appear to be comparable with their U.S. counterparts, although in most instances their reported technology lags somewhat behind that of the U.S. Their open-cycle-generator technology is clearly inferior. On the other hand, their U-25 installation, the first complete MHD power plant in the world, is unique and undoubtedly is providing the Soviets with large-scale engineering experience unavailable to U.S. scientists.

The Soviets took a considerable risk in going to the U-25, a fairly large pilot plant, directly from the experience gained in working with the relatively small U-02 plant, especially since the necessary MHD generator performance had not been demonstrated. The U-25 is designed to operate at 2900° K, Mach 0.9 to 0.95, and 2 Tesla, and to deliver 300 MW(t) for 1000 hours. As of now, the peak temperature reached has been 2730° K; only 5 MW(e) of MHD power has been achieved for durations of one hour. If current U.S. MHD technology were to be incorporated into the U-25, however, the power output could probably be raised to 12 MW(e). The main contribution of the American channel would be to increase segmentation so that the loading could be changed in such a way as to raise generator power to 12 MW(e) and to take advantage of hot electrodes.

While a considerable risk was involved in stepping from the small U-02 plant directly to the U-25 in terms of generator performance, it had great advantages in that long-duration materials testing could be undertaken both in the MHD generator and the auxiliary components under conditions which were representative of commercial MHD and which were capable of being scaled to commercial-sized units. A serious present lack in the U.S. program is a corresponding capability to test materials on both a model-scale and pilot-scale facility, such as the U-25 provides.

The Soviet Union's visible closed-cycle MHD program, although larger than the corresponding U.S. effort, is nevertheless relatively small. Closed-cycle plasma work apparently never reached the large power-production stage (nor the high enthalpy extraction) achieved in the U.S. at General Electric. It is probable that the extensive Soviet preoccupation with plasma instabilities led them to believe that the closed-cycle generator would never operate efficiently, and therefore they apparently deemphasized the effort.

The responsibility for closed-cycle plasma MHD development appears to rest primarily with the Kurchatov Institute, which has a large linear shock tube similar to that at General Electric and two small blowdown facilities. According to private discussions, scientists at that Institute have taken the position that MHD can be suitably mated with a 1500° to 2000° K nuclear reactor, or a fusion reactor. The latter could be a laser fusion device that would heat lithium to 3000° K or higher. The broad scope and low magnitude of the closed-cycle effort indicated by the open literature suggests that the Soviet approach to MHD-nuclear reactor systems is long-range. On the basis of known engineering work, the United States probably leads the USSR in closed-cycle plasma MHD at this time. The U.S. closed-cycle effort, however, has in recent years been considerably curtailed.

The liquid-metal program is more difficult to evaluate. The Soviets have done some work that has not yet been undertaken in the U.S. -- e.g., the operation of complete power systems at actual operating conditions (in the U.S., operating conditions were simulated). The information gained from open sources, the observation of a large number of authors publishing in the field, and the number of participating institutes would

suggest a substantial operation. However, most of the published work [104-110] from institutes other than the Krzhizhanovskiy, the Kurchatov, and the High Temperatures (the big three in MHD research) involve work of a secondary nature on MHD pumps, nozzles, and classical MHD problems, rather than topics critical to generator development. In sum, the Soviet liquid-metal effort is larger than that of the United States at present, but much smaller than the open-cycle effort in either country.

Soviet reticence to discuss their liquid-metal program with U.S. specialists, coupled with apparently planned release of specific information, suggests that at least a portion of their liquid-metal program may have military application. It should be emphasized, however, that they undoubtedly have interest in developing liquid-metal MHD for commercial applications [111-113].

The only ongoing liquid-metal MHD program in the United States, at Argonne National Laboratory, is oriented toward establishing performance levels that are likely to be achieved with the two-phase generator cycle and investigating its feasibility for central-station commercial application, as well as for ship propulsion.

There has been some controversy in the United States in recent years with respect to the relative merits of the various MHD technologies. The present energy crisis and the concomitant need for more efficient conversion technologies have revived interest in MHD technology for commercial power applications. The resulting increased availability of research funds, while still very little in comparison to the funding of other energy programs, generated considerable competition between the proponents of the three basic categories of MHD technology, with each group citing favorable data in support of its approach -- e.g., closed-cycle plasma proponents cite highest enthalpy extraction and lower development costs; liquid-metal specialists cite lower operating temperatures as well as lower development costs. The open-cycle effort, however, has outstripped its two competitors and is being presently conducted on a much larger scale; it appears to be the most promising for baseload central-station applications, particularly if fossil fuels are used. Although they appear to have considerable potential, a major drawback of

the operational characteristics of the closed-cycle and liquid-metal technologies have not yet been clearly and completely demonstrated. There has been little experience with complete two-phase liquid-metal systems, and there are a number of unknowns associated with closed-cycle nonequilibrium MHD. There is a question, for example, of whether the required level of ionization can be maintained over distances sufficiently great to make this scheme practical. Likewise, there has been no demonstration that such a scheme will work with regenerative preheaters where large amounts of impurities introduced by such preheaters can prevent the establishment of nonequilibrium conductivity. A considerable amount of basic work remains to be done to answer these questions, and present experiments are still of very short-time duration (even when compared to the early short-time experiments in open-cycle MHD).

Western interest in the closed-cycle technologies, as evidenced by the open literature, appears to be on the decline. There has been a large decline in recent years in the number of papers submitted in these two subject areas (U.S. contributions especially have declined).

## U.S. AND USSR STATE OF THE ART

It is very difficult to make an accurate comparison of the relative U.S. and USSR state of the art in MHD, for the two countries have followed two distinctly different approaches (mainly in terms of open-cycle work). In the USSR, the emphasis has been on materials development and in the engineering of large installations, with a correspondingly large amount of experience being gained in the handling of MHD systems. This has been made possible by a generous budget and by the favorable attitudes of the people who direct the Soviet program. Power-plant engineers have figured prominently in the Soviet program because of utility support, and this has led to a more engineering-oriented effort than has been the case in the United States, where aerospace-trained personnel have tended to dominate the field. In the United States, a combination of personal interests, projects directed toward short-time military applications, and limited

funds have all led to a much more intensive development of generators and a detailed understanding of their performance. Some imaginative work in materials has also been undertaken and individual components have been studied, but there is as yet no overall systems experience in any way comparable to that now being acquired by the team which operates the U-25. A further aspect of U.S. work has been concentration on the problems of coal-firing and also the environmental implications of MHD, and here the United States enjoys a considerable lead. This situation quite naturally forms a basis for cooperation in which the United States can exchange its high technology expertise in MHD (i.e., far greater understanding of generator design) for the engineering and plant experience acquired by the Soviet groups, and together, the two countries can bring MHD to the point of technical success more quickly than would be possible independently.

Enough experience has been gained with open-cycle MHD to make it possible to have a gas-fired pilot plant operating successfully (in the case of the U-25 with an output of about 15 MW for a thousand hours) within a few years, and the engineering data for a coal-fired pilot plant to be constructed in the United States in the late 1970s is rapidly being accumulated. The goal of commercial service for MHD by 1985 remains a realistic one, provided adequate funding is forthcoming and no unforeseen setbacks occur.

In the special-applications area, U.S. pulsed-power generator technology is sufficiently developed to contemplate realistically the construction of a ground-based prototype to demonstrate feasibility. This has come about through advances in superconducting-magnet technology and generator-channel fabrication. It must be emphasized, however, that the U.S. high-field superconducting magnets for MHD (5-6 Tesla) have not yet been constructed successfully and that all magnets specifically intended for MHD service (except for a very recent Japanese development) have failed to provide fields above 4 Tesla, although 5 to 6 was called for in some designs. Four Tesla is sufficient for a high-performance generator, but it is inadequate for baseload fossil-fired units where preheated air does not yield as high a flame temperature as oxygen and

exotic fuel. Of the many technological areas requiring further engineering development, the superconducting magnet is certainly an important one. If Soviet MHD magnet and generator technology has reached a corresponding level, there is no indication from the commercial program. Indeed, in the U.S.-USSR MHD exchange program recently negotiated, the Soviets pressed strongly for a superconducting magnet for the U-02.

This presents a rather curious picture of the present level of Soviet superconducting-magnet technology. The USSR is known to have a first-rate superconductivity program* and to have made some advances which are not reflected in their MHD magnet technology. Aside from a small superconducting magnet used with an explosive-driven generator [39, 40] (Fig. 21) and a still smaller cold-bore magnet [40, 114] (Fig. 25) constructed at the Institute of High Temperatures, the Soviets are not

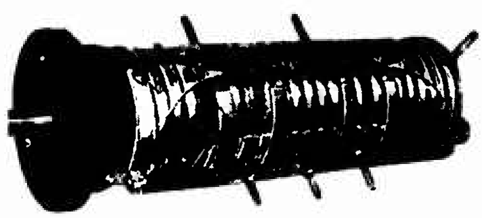

Fig. 25 -- Small cold-bore saddle-coil superconducting magnet constructed by the Institute of High Temperatures [114]

*See Y. Ksander and S. Singer, *Advanced Concepts of Superconductivity: A Comparative Review of Soviet and American Research. Part I. High-Temperature Superconductivity*, The Rand Corporation, R-1401-ARPA, January 1974.

known to have constructed any superconducting magnets specifically for MHD applications. U.S. visitors to the Krzhizhanovskiy Power Institute were told that a superconducting magnet was being developed for the ENIN-2, and they were shown a schematic drawing of it (Fig. 18), but it is not known to have been constructed. Yet, the Soviets have recognized for a number of years the necessity of constructing such magnets for MHD applications [115]. The probable cause of this situation is either that their MHD institutes have little or no contact with those involved with superconductivity or that they have had particular difficulty in constructing large-core superconducting magnets, as is implied in some of their publications [115].

Professor Mori of Japan reported recently in a letter to members of the International MHD Liaison Group that the Japanese magnet for their Mark VI facility had attained a field of 4.75 Tesla out of a design goal of 5 Tesla. This magnet, which has a bore nearly 2 meters long, will be used in the imminent first high-field long-duration MHD generator tests. The Japanese Mark VI is similar in mass flow to the Avco Mark VI and has hitherto been operated, like their Mark II facility, with a conventional magnet of about 2.5 Tesla.

IMPLICATIONS OF MHD FOR MILITARY TECHNOLOGY

Prominent among the applications under consideration have been pulsed-power missiles and wind tunnels and power supplies for space platforms. In these cases, the overall systems themselves have not developed to the point where power supplies were needed. In the case of airborne battlefield illumination, MHD technology was simply not sufficiently advanced to meet the time requirements of the Vietnam war. The technology fallout via the materials used in MHD generator ducts, the fuel systems, and the component fabrication techniques is insignificant, as they are similar to those used in other high-temperature technologies. The powering of large accelerators and fusion magnets is more of a convenience than a necessity. The TVA has demonstrated at the Arnold Engineering Development Center that it can supply large peak demands from a standard electric transmission network. However, operation with MHD would make it possible to provide electric energy if the regular supply were to be interrupted in an emergency.

Commercial programs generally require the development of an MHD generator with a relatively complex cycle, while military applications require a simple unit which emphasizes high performance. In general, commercial- and military-generator operating experiences in the development phase have much in common, but the design details differ considerably.

The limitation on commercial systems is cost: The use of oxygen is uneconomical, and therefore the necessary high-enthalpy working fluid must be produced using fossile fuel with preheated air. For this reason, the MHD unit must be designed for maximum enthalpy extraction, and the capital investment in an MHD plant becomes large. On the other hand, the military generator is required to be compact and to extract as much electrical energy as possible from the flowing gas; therefore, high energy densities are needed. High energy densities are achieved by the use of pure oxygen and chemical fuels which lead simultaneously to high conductivity and high velocity. High enthalpy extraction is not the prime requisite in this case (unless fuel economy is extremely important); thus, the experience gained with large military generators is not directly applicable to commercial situations. For this reason, many workers in the MHD field have recommended that enthalpy extraction be demonstrated as part of the pilot-scale hardware development.

A promising military application is ship propulsion, and here liquid-metal MHD appears to have the potential to yield higher overall conversion efficiencies than present steam turbo machinery and mechanical drives, at drastically reduced noise levels. As a first step in this direction, it is necessary to experiment with various liquid-metal MHD systems in which heat energy is converted into electrical energy through a liquid metal. For the two-phase system favored for this application, apparently no such demonstration has yet been undertaken in either the United States or the USSR, though this is presumably the purpose of the loop at the ENIN-II. Argonne National Laboratory is currently building a high-temperature two-phase MHD generator and will test it on a sodium facility at 1000° F.

## Appendix

## RECORD OF THE FIRST MEETING OF THE U.S.-USSR STANDING STEERING COMMITTEE FOR THE SCIENTIFIC AND TECHNICAL COOPERATIVE DEVELOPMENT OF COMMERCIAL SCALE OPEN-CYCLE MHD POWER PLANTS

The U.S.-USSR Standing Steering Committee for the Scientific and Technical Cooperative Development of Commercial Scale Open-Cycle MHD Power Plants (hereinafter referred to as the Committee), held its first meeting in Washington, D.C., July 9 to 19, 1973. This meeting was held in implementation of the understanding regarding open-cycle MHD cooperation (hereinafter referred to as the Understanding), reached between representatives of the U.S.-USSR Joint Working Group on Energy in Moscow on October 6, 1972, and endorsed as a cooperative program (hereinafter referred to as the Program), by the U.S.-USSR Joint Commission on Scientific and Technical Cooperation in Washington, D.C., on March 21, 1973.

I. The Committee, at its first meeting, considered all aspects of the Program and affirmed the following points:

   A. The ultimate goal of the Program is to achieve the design, construction, and initial operation of one or more commercial scale units in the two countries.

   B. The achievement of this goal in each country will be more quickly and surely realized at lower cost if the work is pursued jointly.

   C. The MHD power generation process has important potential for the better utilization of the fossil fuel resources, especially coal, of the two countries with substantially increased thermal efficiency and dramatically reduced environmental pollution relative to current electric power technology.

   D. The cooperation will have maximum effectiveness if it is conducted as an accelerated program within a time frame

consistent with current predictions for construction and initial commercial operation in the early 1980s.

II. The Committee confirmed the Program, predicated upon the availability of annual appropriations from the Congress of the United States, and following approved funding by the official organs of the USSR. The Committee took note that the following specific activities had been proposed for the Program:

A. Mutual Exchange of Technical Information

1. Exchange of information by reports, preprints, and other items.
2. Joint colloquia in both countries at least once a year.
3. Exchange of specialists for short visits to laboratories and installations.

B. Joint Theoretical and Experimental Research

1. Development of joint programs for theoretical research and the conducting of agreed research projects.
2. Development of a joint experimental research program using the following installations:

   a. United States

   Mark VI (Avco-Everett); UTSI-II (University of Tennessee); MHD Coal Burning Facilities (Bureau of Mines, Bruceton, Pa.); High Field MHD Magnet (Stanford University), and others under the Office of Coal Research Industry-sponsored MHD program.

   b. USSR

   U-02, U-25, and others (Institute for High Temperatures); ENIN-2 and others (Krzhizhanovskiy Power Institute). Other installations, as they are developed, will be added by both countries.

3. Testing of equipment produced in one country in the facilities of the other country.

   a. Long duration tests of U.S. channel sections in U-02.
   b. Tests of U.S. material and air preheater construction elements in U-02.

c. Tests of U.S. electrode replenishment technique in U-02.

d. Supply by U.S. of a 4-Tesla superconducting magnet for U-02 for testing both USSR and U.S. long duration channels.

e. Supply and testing of U.S. channel and its components in U-25.

f. Supply and testing of U.S. coal combustion chambers and other appropriate components for ENIN-2.

g. Supply (according to the suggested equipment lists) of diagnostic equipment from Institute for High Temperatures to be tested on the Avco-Everett Mark VI.

h. Exchange of other diagnostic equipment as is mutually agreed upon.

C. Cooperative Design of MHD Power Plants

1. Choice of reference parameters for base and peaking MHD power stations and determination of power levels of fuel, oxidant, and other items.

2. Preliminary design work and determination of station economics.

3. Preparation of a program plan for the design and construction of the first commercial scale MHD units for base and peaking use in both the USSR and the United States.

D. Evaluation of the Feasibility of Undertaking a Joint Program for the Construction and Initial Operation of Commercial Scale MHD Units for Base and Peak Loads.

III. The Committee agreed that in order to fulfill the Program, work is to be undertaken in stages. The following tasks were selected as first priority items for the first six months of the Program.

A. By the United States

1. Conceptual design of U-25 channel.
2. Specification of materials to be tested on U-02.
3. Conceptual design of 4-Tesla superconducting magnet for U-02.
4. Provision of engineering and materials data obtained from operating facilities for joint comparison and evaluation.
5. Specification of diagnostic equipment to be supplied to the USSR.

B. By the USSR

1. Conceptual design of diagnostic equipment (to be selected by the United States from a list supplied by the USSR).
2. Provision of engineering and materials data obtained from operating facilities for joint comparison and evaluation.
3. Supply of supplementary data for conceptual design of U.S. channel for U-25.
4. Supply of supplementary data for conceptual design of superconducting magnet for U-02.
5. Supply of initial data for the design of a coal combustion chamber.
6. Organization of the first U.S.-USSR colloquium in Moscow.

C. The above items represent the first stage of the Program. Projected target dates for completion of specific projects in the Program are as follows:

| | Target Date |
|---|---|
| 1. Design and construction of a U.S. channel for experimental work in the U-25 ........ | 1975 |

| | | Target Date |
|---|---|---|
| 2. | Design, construction, and installation of a U.S. 4-Tesla superconducting magnet for experimental work in the U-02 ......... | 1975 |
| 3. | Materials and channel element testing in the U-02 ................................ | 1974 |
| 4. | Design, construction, and testing of U.S. coal burner on a USSR installation ........ | 1975 |
| 5. | Cooperative design of pilot and commercial scale plants ............................ | 1976 |

Detailed program plans for the projects will be developed by both sides for consideration at the next meeting of the Committee.

IV. The Committee took note of the following developments since the negotiation of the understanding:

1. The USSR prepared and transmitted through its delegation to the present meeting of the Committee programs and reference data to implement the Program. To initiate the exchange of information, the USSR delegation provided the complete report prepared by the Institute of High Temperatures on the first stage of the investigation conducted with the U-25 installation.
2. The United States arranged a series of five ad hoc working group meetings during the first meeting of the Committee. These were attended by a total of thirty-four U.S. specialists and covered technical areas provided in the Program as follows:
   a. System Studies Power Plant design;
   b. Coal Combustion and Combustors;
   c. Materials Studies;
   d. Generator Channels for U-02 and U-25 Installations;
   e. Superconducting magnet for the U-02 Installation.

3. The present program of MHD research and development in the two countries continues to develop and to yield encouraging results. In the USSR, the U-25 pilot plant has now achieved 4500 kilowatts of electrical output while the U-02 installation has continuously operated generator channels for 300 hours and has achieved 15000 hours of operation with the preheater in the temperature range 1700-2000° C. In the United States, the Mark VI installation has accumulated over 50 hours of satisfactory operation with hot electrodes, and the UTSI-II facility has successfully operated an MHD generator for over one hour on the products of the combustion of coal with oxygen.

V. The Committee supports the proposal by the United States to expand the cooperation to fundamental areas of magnetohydrodynamic power generation. The Committee endorses the preparation of a letter by the U.S. National Academy of Sciences to the USSR Academy of Sciences making this proposal.

VI. The Committee agrees that the receiving side will cover in-country expenses of visitors, including necessary living, travel, and medical expenses, but recognizes that administrative authority must be obtained before this can be fully implemented. Both sides shall undertake to exert their best efforts to reach a final agreement on this point at the next meeting of the Committee. Nevertheless, to enable the tasks set forth in III A and B above to be undertaken and to conduct both the second meeting of the Committee and the first joint Colloquium, each side agrees to provide in-country expenses as specified above for up to the equivalent of one man year of effort for the period until the next meeting of the Committee.

VII. The Committee established the schedule of its own meetings and colloquia as follows:

1. The Committee will meet biannually, in April or May in the USSR and in October or November in the United States.
2. Colloquia will be held annually, alternately in the two countries, starting with the Soviet Union in 1974.
3. Ad hoc working groups are to be organized and will meet as necessary.
4. To effect the transition to this schedule, the next Steering Committee meeting and the first Colloquium will be held in Moscow in January or February 1974.

VIII. The Committee wishes to record that it completed its work on establishing the first phase of the Cooperation and initiating agreed activities in the frank and friendly atmosphere which is the custom in relations between workers in the USSR and United States in the field of MHD.

A. E. Sheindlin
Responsible from the USSR for
Cooperation with the United
States in MHD

G. R. Hill
Responsible from the United
States for Cooperation with
the Soviet Union in MHD

Prepared in English and Russian,
both texts being equally authentic.
Washington, D.C.
July 19, 1973

## REFERENCES


1. Joint ENEA/IAEA International Liaison Group on MHD Electrical Power Generation, *MHD Electrical Power Generation: 1967 Status Report,* 1967.

2. Joint ENEA/IAEA International Liaison Group on MHD Electrical Power Generation, *MHD Electrical Power Generation: 1969 Status Report,* 1969.

3. Joint ENEA/IAEA International Liaison Group on MHD Electrical Power Generation, *MHD Electrical Power Generation: 1972 Status Report,* 1972.

4. *Investigation of Liquid-Metal MHD Power Systems,* Office of Naval Research, Report ANL/ETD-72-06, Contract NAonr-19-72, December 1972.

5. Mattsson, A., et al., "Performance of a Self-Excited MHD Generator," *Mechanical Engineering,* November 1966.

6. Teno, J., et al., "Studies with a Hall Configuration MHD Generator," *Proceedings of the Tenth Symposium on the Engineering Aspects of MHD,* Cambridge, Massachusetts, March 1969.

7. *Airborne MHD Generator Development,* Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, Technical Report AFAPL-TR-69-3, 1969.

8. Hals, F. A., and W. D. Jackson, "Systems Analysis of Central Station MHD Power Plants," *Proceedings of the Fifth International Conference on MHD Electrical Power Generation,* Munich, April 19-23, 1971.

9. Zauderer, B., paper presented at the November 1973 ASME Winter Annual Meeting, Detroit.

10. Nemets, I. I., A. Ye. Nestertsov, G. V. Kukolev, et al., "Interaction of Magnesium Oxides with Aluminum Compounds," *Neorganicheskiye materialy,* Vol. 9, No. 3, 1973.

11. Sheindlin, A. E., I. S. Belevich, and I. G. Kozhevnikov, "Enthalpy and Specific Heat of Niobium Carbides at High Temperatures," *Teplofizika vysokikh temperatur,* Vol. 11, No. 1, 1973.

12. Sheindlin, A. E., I. S. Belevich, and I. G. Kozhevnikov, "Enthalpy and Heat Capacity of Boron Carbide in the 273-2600° K Range," *Teplofizika vysokikh temperatur,* Vol. 10, No. 2, 1972.

13. Sheindlin, A. E., I. S. Belevich, and I. G. Kozhevnikov, "Enthalpy and Specific Heat of Tantalum Carbide in the 273-360 K Range," *Teplofizika vysokikh temperatur*, Vol. 10, No. 3, 1972.

14. Shpilrayn, Ye. Ye., D. N. Kagan, and L. S. Barkhatov, "Enthalpy of Fused Boron Oxide at High Temperatures," *Teplofizika vysokikh temperatur*, Vol. 9, No. 1, 1971.

15. Shpilrayn, Ye. Ye., D. N. Kagan, and L. S. Barkhatov, "Thermodynamic Properties of Liquid- and Solid-Phase Beryllium Oxide," *Teplofizika vysokikh temperatur*, Vol. 9, No. 5, 1971.

16. Samsonov, G. V., V. M. Sleptsov, G. G. Gnesin, et al., "Research on Materials for Manufacturing of Open-Cycle MGDT Electrodes," *Fifth International Conference on MHD Electrical Power Generation*, Vol. 1, Munich, April 19-23, 1971.

17. Tishchenko, Z. V., Yu. S. Kravchenko, and N. D. Butskiy, "Testing Metals in a High-Temperature Combustion-Product Flow," *Teplofizika vysokikh temperatur*, Vol. 9, No. 2, 1971.

18. Vysotskiy, D. A., M. D. Petrov, A. I. Rekov, et al., "Test Results on Insulating and Electrode Materials in a Plasma Jet," *Teplofizika vysokikh temperatur*, Vol. 10, No. 3, 1972.

19. Sheindlin, A. E., et al., *Major Results of Scientific Research in 1972 at the Institute of High Temperatures of the USSR Academy of Sciences*, Izd. Nauka, Moscow, 1973.

20. *MHD for Central Station Power Generation: A Plan for Action*, Report of the OST Panel on MHD, June 1969.

21. Hill, George, "Keynote Address on Energy Conversion," *Proceedings of the Conference on Research for the Electric Power Industry*, Washington, December 11-14, 1972.

22. *Electric Utilities Industry Research and Development Goals Through the Year 2000*, Report of the R&D Task Force to the Electric Research Council, June 1971.

23. Dicks, J. B., R. H. Eustis, A. R. Kantrowitz, K. A. Roe, and S. Way, *Jointly Prepared Statement on a National Program for MHD Central Power Generation*, May 1973.

24. Kirillin, V. A., A. E. Sheindlin, B. Ya. Shumyatsky, et. al., "Investigations at U-02 MHD Plant -- Some Results," *Fifth International Conference on MHD Electrical Power Generation*, Vol. 1, Munich, April 19-23, 1971.

25. Ovcharenko, V. A., "MHD Conversion of Thermal Energy into Electrical," *SSLA*, No. 6, Moscow, June 1973.

26. Kirillin, V. A., et al., "Some Data Obtained with an Experimental MHD Power Plant," *Proceedings of the Eighth Symposium on the Engineering Aspects of MHD*, Stanford, March 28-30, 1967.

27. Kirillin, V. A., A. E. Sheindlin, B. Ya. Shumyatsky, "The U-02 Installation Under Extended Continuous Operating Conditions," *Teplofizika vysokikh temperatur*, Vol. 9, No. 5, 1971.

28. Sheindlin, A. E., et al., *Studies with the U-25 Installation, Part I*, Institute of High Temperatures, Moscow, June 1973.

29. Sheindlin, A. E., "New Approaches to Electric Power Development," *Vestnik AN SSSR*, Vol. 38, No. 11, 1968.

30. Medin, S. A., V. A. Ovcharenko, and Ye. Ye. Shpilrayn, "Problems in MHD Energy Conversion," *Teplofizika vysokikh temperatur*, Vol. 10, No. 2, 1972.

31. Nikitenko, K., "Future of MHD Generators," *Nauka i tekhnika*, No. 4, 1973.

32. Gorbunova, N. I., "Moscow Symposium on MHD Plants," *Teplofizika vysokikh temperatur*, Vol. 9, No. 1, 1971.

33. Sirotkina, V. P., and R. S. Skibitskaya, eds., *Major Results of Scientific Research in 1971 at the Institute of High Temperatures of the USSR Academy of Sciences*, Izd. Nauka, Moscow, 1972.

34. Kirillin, V. A., et al., "A 25-MW MHD Pilot Plant," *Ninth Symposium on Engineering Aspects of MHD*, Tullahoma, Tennessee, April 3-5, 1968.

35. Rudins, George, "Soviet Computers: An Historical Survey," *Soviet Cybernetics Review*, The Rand Corporation, Vol. 4, No. 1, 1970.

36. Zhimerin, D. G., V. A. Bashilov, Yu. V. Makarov, et al., "Investigation of Cooled Channel on ENIN-2 Installation," *Fifth International Conference on MHD Electrical Power Generation*, Vol. 1, Munich, April 19-23, 1971.

37. Zhimerin, D. G., et al., "Results of Electrophysical Studies on a Section of the ENIN-2 MHD Generator," *Proceedings of the Eleventh Symposium on the Engineering Aspects of MHD*, Pasadena, March 24-26, 1970.

38. Shvets, I. T., A. N. Milyakh, E. P. Strashynin, et al., "Experimental MHD Generator of the Academy of Sciences and Ministry of Energetics of the Ukrainian SSR," *Fifth International Conference on MHD Electrical Power Generation*, Vol. 1, Munich, April 19-23, 1971.

39. Kirillin, V. A., et al., "Explosive Magnetohydrodynamic Generator with a Superconductive Magnetic System," *Doklady AN SSSR: Seriya fizicheskaya* Vol. 185, No. 2, 1969.

40. Sychev, V. V., "Some Problems in Developing Superconducting Magnet Systems," *Izvestiya AN SSSR: Energetika i transport*, No. 4, 1972.

41. Wu, Y. C. L., et al, "Investigation of a Diagonal Conducting Wall Generator," *Thirteenth Symposium on the Engineering Aspects of MHD*, Stanford, March 26-28, 1973.

42. Eustis, R. H., and R. Kessler, "Measurement of Current Distributions and the Effect of Electrode Configuration on MHD Generator Performance," *Fifth International Conference on MHD Electrical Power Generation*, Vol. 1, Munich, April 19-23, 1971.

43. Teno, J., et al., "Long Duration Electrode for Open-Cycle MHD Generators," *Proceedings of the Eighth Symposium on the Engineering Aspects of MHD*, Stanford, March 28-30, 1967.

44. Zauderer, B., and E. Tate, "Experiments in a Large, Nonequilibrium MHD Generator with Cesium-Seeded Noble Gases and Heated Electrodes," *Fifth International Conference on MHD Electrical Power Generation*, Vol. 2, Munich, April 19-23, 1971.

45. Zauderer, B., and E. Tate, "High Enthalpy Extraction Experiments in a Large Nonequilibrium MHD Generator," *Thirteenth Symposium on the Engineering Aspects of MHD*, Stanford, March 26-28, 1973.

46. Malikov, M. M., et al., "Faraday-type Channel with Essentially Nonequilibrium Plasma," *Fifth International Conference on MHD Electrical Power Generation*, Vol. 2, Munich, April 19-23, 1971.

47. Glushkov, I. S., et al., "Investigation of Nonequilibrium Plasma in a Pressure Gradient Flow," *Fifth International Conference on MHD Electrical Power Generation*, Vol. 2, Munich, April 19-23, 1971.

48. Velikhov, E. P., and A. M. Dykhne, *Proceedings of the Sixth Joint Symposium on Ionization Phenomena in Gases*, Paris, 1963.

49. Velikhov, E. P., et al., "Numerical Solution of Ionization Instability," *Fifth International Conference on MHD Electrical Power Generation*, Vol. 2, Munich, April 19-23, 1971.

50. Dykhne, A. M., "Nonlinear Plasma Phenomena Connected with Ionization Instability," *Fifth International Conference on MHD Electrical Power Generation*, Vol. 2, Munich, April 19-23, 1971.

51. Biberman, L. M., et al., "On Determining the Characteristics of an MHD Generator Operating on Nonequilibrium Plasma," *Teplofizika vysokikh temperatur*, Vol. 9, No. 1, 1971.

52. Millionshchikov, M. D., et al., "Potential Use of Gas-Turbine Plants and MHD Generators in Atomic Power Stations with High Temperature Gas-Cooled Reactors," *Teplofizika vysokikh temperatur*, Vol. 8, No. 2, 1970.

53. Buznikov, A. E., et al., "Experimental Investigation of Non-equilibrium Effects in an MHD Generator, " *Teplofizika vysokikh temperatur*, Vol. 9, No. 5, 1971.

54. Sheindlin, A. E., et al., "Experimental Investigation of the Effect of Boundary Layers on the Characteristics of an MHD Generator Over a Wide Range of Hall Numbers," *Teplofizika vysokikh temperatur*, Vol. 9, No. 2, 1971.

55. Buznikov, A. E., et al., "Start Facility for Studying MHD Generators Using Inert Gases with Alkaline Seeding," *Teplofizika vysokikh temperatur*, Vol. 8, No. 5, 1970.

56. Buznikov, A. E., et al., "Experimental Study of the Characteristics of a Nonequilibrium MHD Generator," *Teplofizika vysokikh temperatur*, Vol. 11, No. 3, 1973.

57. Sheindlin, A. E., et al., *Major Results of Scientific Research in 1972 at the Institute of High Temperatures of the USSR Academy of Sciences*, Izd. Nauka, Moscow, 1973.

58. Sheindlin, A. E., et al., *Major Results of Scientific Research in 1971 at the Institute of High Temperatures of the USSR Academy of Sciences*, Izd. Nauka, Moscow, 1972.

59. Maksimov, A. M., "An Electric-Discharge Shock Tube as a Plasma Flow Source for MHD Generators," *Teplofizika vysokikh temperatur*, Vol. 9, No. 5, 1971.

60. Gutman, I. I., et al., "Thermodynamic Efficiency of $UF_6$ MHD Plants," *Teplofizika vysokikh temperatur*, Vol. 9, No. 6, 1971.

61. Goryachev, V. L., and A. S. Remennyy, "Calculation of the Parameters of a Plasma of Pure Inert Gases for a Nonequilibrium MHD Generator," *Teplofizika vysokikh temperatur*, Vol. 9, No. 5, 1971.

62. Motornenko, A. P., et al., "An MHD Generator on a Nonequilibrium Plasma Generated by VHF Ionization," *Ukrainskiy fizicheskiy zhurnal*, Vol. 18, No. 6, 1973.

63. Bertolini, E., et al., "Closed-Cycle MHD Subsonic Power Generation Experiments at Frascati," *Thirteenth Symposium on the Engineering Aspects of MHD*, Stanford, March 26-28, 1973.

64. Petrick, M., and K. Lee, *Liquid MHD Power Cycle Studies*, Argonne National Laboratory, ANL-6954, June 1965.

65. Shpilrayn, Ye. Ye., et al., "Thermodynamic Analysis of New Cycles for Liquid-Metal MHD Generators," *Symposium on the Production of Electrical Energy by Means of MHD Generators*, IAEA, Vienna, July 1968.

66. Basov, S. N., P. L. Kirillov, and V. I. Subbotin, "Injection of Liquid Metals in MHD Converters," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation*, Vol. 2, Salzburg, Austria, July 4-8, 1966.

67. Yakimovich, K. A., Ye. Ye. Shpilrayn, and Yu. M. Syaskin, "Thermodynamics of a Two-Component Liquid-Metal Power MHD Assembly with Injector," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation*, Vol. 2, Salzburg, Austria, July 4-8, 1966.

68. Kirillov, P. L., and V. I. Subbotin, "Measuring the Electrical Conductivity of a Liquid-Vapor Potassium Mixture," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation*, Vol. 2, Salzburg, Austria, July 4-8, 1966.

69. Bogomolov, B. G., S. D. Kukhovlinov, E. V. Chernykh, and E. M. Shelkov, "Results of a Research on a Single-Component System for a Liquid-Metal MHD Energy Converter," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation*, Warsaw, July 1968.

70. Boldyrev, V. M., A. E. Morozov, P. P. Orlov, Yu. M. Syaskin, Ye. Ye. Shpilrayn, and K. A. Yakimovich, "Thermodynamic Analysis of New Cycles for Liquid-Metal MHD Generators," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation*, Warsaw, July 1968.

71. Kozlov, V. B., "Thermodynamics of Multi-Stage Injector MHD Convertor Liquid-Metal Cycle," *Twelfth Symposium on the Engineering Aspects of Magnetohydrodynamics*, Argonne, Illinois, March 27-29, 1972.

72. Bashkatov, V. A., V. M. Boldyrev, A. E. Morozov, P. P. Orlov, I. M. Postnikova, Yu. M. Syaskin, Ye. Ye. Shpilrayn, and K. A. Yakimovich, "The Analysis of Liquid-Metal Plants with a Piston and Homogeneous Two-Phase Flow in the Generator," *Fifth International Conference on MHD Electrical Power Generation*, Vol. 3, Munich, April 19-23, 1971.

73. Morozov, A. E., I. M. Postnikova, Yu. M. Syaskin, Ye. Ye. Shpilrayn, and K. A. Yakimovich, "Thermodynamic Analysis of the Cycles of a Double-Phase-Flow MHD Generator in MHD Plants," *Twelfth Symposium on the Engineering Aspects of Magnetohydrodynamics*, Argonne, Illinois, March 27-29, 1972.

74. Lielpeter, Y. Y., "Applicability of the Electrodynamic Approximation in the Theory of Liquid-Metal Induction Converters," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation*, Vol. 2, Salzburg, Austria, July 4-8, 1966.

75. Baranov, G. A., V. F. Vasilyev, V. A. Glukhikh, B. G. Karasev, I. R. Kirillov, and I. V. Lavrentyev, "Experimental Investigations on Liquid-Metal MHD Generators," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation*, Warsaw, July 1968.

76. Chepovetsky, A. G., "Study on Electromagnetic Phenomena in Cylindrical Inductive MHD Converter," *Fifth International Conference on MHD Electrical Power Generation*, Vol. 3, Munich, April 19-23, 1971.

77. Bakanov, Yu. A., L. M. Dronnik, V. E. Strizhak, I. M. Tolmach, and E. E. Yantovskiy, "Study of an Induction-Type Liquid-Metal MHD Generator," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation,* Warsaw, July 1968.

78. Baranov, G. A., V. F. Vasilyev, V. A. Glukhikh, B. G. Karasev, I. R. Kirillov, and I. V. Lavrentyev, "Theoretical and Experimental Investigations of Liquid-Metal MHD Generators," *Fifth International Conference on MHD Electrical Power Generation,* Munich, Vol. 4, April 19-23, 1971.

79. Dmitriyev, K. I., P. P. Mikhailov, and V. S. Presnyakov, "Experimental Investigation of the Magnetohydrodynamic Flow of a Liquid Metal in a Rectangular Duct with Conducting Walls," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation,* Vol. 2, Salzburg, Austria, July 4-8, 1966.

80. Lavrentyev, I. V., "End Effect in MHD Ducts with Non-Conducting Partitions," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation,* Warsaw, July 1968.

81. Birzvalk, Yu. A., "A Method for Calculating Conduction-Type Liquid-Metal MHD Machines Employing Partitions," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation,* Warsaw, July 1968.

82. Dmitriyev, K. I., E. A. Zotova, I. A. Ivanov, V. S. Presnyakov, and F. R. Ulinich, "Investigation of a Liquid-Metal-Jet MHD Generator," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation,* Warsaw, July 1968.

83. Kim, K. I., "The Rayleigh-Taylor Instability in Synchronous Liquid-Metal MHD Generators, and Methods of Suppressing It," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation,* Warsaw, July 1968.

84. Stechkina, I. B., and F. R. Ulinich, "Hydrodynamics of Flow of Two-Component Mixtures in Nozzles," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation,* Vol. 2, Salzburg, Austria, July 4-8, 1966.

85. Aladiev, I. T., I. S. Vartazarov, V. A. Pakhorskiy, and S. V. Teplov, "Stimulating Conditions of Double-Phase Nozzles," *Fifth International Conference on MHD Electrical Power Generation,* Vol. 3, Munich, April 19-23, 1971.

86. Aladiev, I. T., I. M. Pchelkin, and S. V. Teplov, "Investigation of Two-Phase Naval Nozzles," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation,* Warsaw, July 1968.

87. Vainshtein, S. I., A. F. Gandelsman, A. P. Sevastyanov, Ye. Ye. Shpilrayn, K. A. Yakimovich, V. S. Danilin, Yu. F. Kalinin, and G. V. Ciklaury, "Starting Up of a Steam-Water Injector with Small Diffuser Throat Cross Section and Performance of a Nozzle with Evaporating Liquid," *Fifth International Conference on MHD Electrical Power Generation,* Vol. 3, Munich, April 19-23, 1971.

88. Aladiev, I. T., S. V. Teplov, and I. M. Tolmach, "Experimental Potassium MHD Installation of 1 kW," *Fifth International Conference on MHD Electrical Power Generation*, Vol. 3, Munich, April 19-23, 1971.

89. Vainshtein, S. I., A. F. Gandelsman, V. A. Ryabtsev, A. P. Sevastyanov, A. P. Shadeyev, Ye. Ye. Shpilrayn, and K. A. Yakimovich, "Start-Up of a Steam-Water Injector by Means of a Moving Diffuser and Outer Performances Thereof," *Twelfth Symposium on the Engineering Aspects of Magnetohydrodynamics*, Argonne, Illinois, March 27-29, 1972.

90. Space Program Summaries, Jet Propulsion Laboratory, Nos. 37-17 through 37-65.

91. Petrick, M., J. L. Roberts, G. Lambert, and E. Spleha, *Analytical and Experimental Studies of Single- and Two-Phase Liquid-Metal Faraday Generators*, prepared for the Air Force Aero Propulsion Laboratory, Technical Report AFAPL-TR-68-93, August 1968.

92. Petrick, M., and K. Y. Lee, "Performance Characteristics of a Liquid-Metal MHD Generator," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation*, Vol. 2, pp. 953-970, Paris, July, 1964.

93. Petrick, M., "MHD Generators Operating with Two-Phase Liquid-Metal Flows," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation*, Salzburg, Austria, July 4-8, 1966.

94. Petrick, M., and J. J. Roberts, "Analytical and Experimental Studies of Liquid Metal Faraday Generators," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation*, Warsaw, July 1968.

95. Petrick, M., L. C. Pittenger, E. S. Pierson, and R. Cole, *Annual Report on Experimental Two-Phase Liquid-Metal Magnetohydrodynamic Generator Program*, prepared for Office of Naval Research, ANL-ENG-73-02, June 1973.

96. Petrick, M., W. E. Amend, R. Cole, J. C. Cutting, and L. C. Pittenger, *Annual Report on Experimental Two-Phase Liquid-Metal Magnetohydrodynamic Generator Program*, prepared for Office of Naval Research, ANL-ETD-72-06, December 1972.

97. Petrick, M., W. E. Amend, H. C. Stevens, and P. V. Dauzvardis, *Annual Report on Investigation on Liquid-Metal Magnetohydrodynamic Power Systems*, prepared for Office of Naval Research, ANL-ETD-72-06, December 1972.

98. Velikhov, E. P., et al., *An Experimental Rankine-Cycle MHD Facility (Construction and Technological Problems)*, Kurchatov Institute of Atomic Energy (IAE-2087), Moscow, 1971

99. Seikel, G. R., and L. D. Nichols, *The Potential of Nuclear MHD Electric Power Systems*, NASA Technical Memorandum X-67829, June 1971.

100. Bazeyev, E. T., L. S. Bezusy, K. I. Kim, V. E. Pavlenko, I. M. Postnikova, and G. M. Shchegolev, "Liquid-Metal MHD Systems with Laminar Flow and Electric Power Extraction Based on the Synchronous Principle," *Proceedings of the Symposium on Magnetohydrodynamic Electrical Power Generation*, Warsaw, July 1968.

101. Rukhadze, A. A. "High-Current Electron Beams," *Vestnik AN SSSR*, Vol. 42, No. 1, 1972.

102. *Nedelya*, September 3-9, 1973.

103. Dicks, J. B., "Review of MHD Power Situation," *ASME Winter Annual Meeting*, Washington, November 28-December 2, 1971.

104. Khozyaynov, A. E., "Transient Processing in Ducts of Conduction MHD Generators with Nonlinear Inductance in the External Circuit," *Zhurnal tekhnicheskoy fiziki*, Vol. 39, No. 1, 1969.

105. Gnatyuk, V. V., et al., "On the Transition from Laminar to Turbulent Flow Regimes in Channels with Conducting Walls," *Magnitnaya gidrodinamika*, No. 3, 1968.

106. Kukin, I. K., and O. S. Pankratov, "Experimental Study of a Laminar MHD Flow of an Incompressible Fluid in a Diffuser," *Magnitnaya gidrodinamika*, No. 1, 1968.

107. Andreyev, A. M., and V. A. Glukhikh, "Selection of Optimum Relationships in Liquid-Metal Induction Pumps," *Magnitnaya gidrodinamika*, No. 2, 1968.

108. Baranov, G. A., V. F. Vasilyev, V. A. Glukhikh, et al., "Theoretical and Experimental Investigations of Liquid-Metal MHD Generators," *Fifth International Conference on MHD Electrical Power Generation*, Vol. 4, Munich, April 19-23, 1971.

109. Kozyrenko, V. Ye., and V. A. Teplyakov, "Laminar MHD Flow of an Incompressible Fluid in a Flat Duct of Varying Width," *Magnitnaya gidrodinamika*, No. 2, 1969.

110. Vasilyev, A. S., and V. A. Teplyakov, "Experimental Investigation of the Effect of a Transverse Magnetic Field on the Flow in a Channel with Electrodes," *Magnitnaya gidrodinamika*, No. 1, 1969.

111. Shpilrayn, Ye. Ye. "Certain Technical and Economic Aspects of Using Liquid-Metal MHD Plants in Large-Scale Power Engineering," *Symposium on MHD Plants for Direct Conversion of Thermal Energy into Electrical*, Institute of High Temperatures, Moscow, October 12-16, 1970.

112. Bashkatov, V. A., V. M. Boldyrev, A. E. Morozov, et al., "The Analysis of Liquid-Metal MHD Plants with a Piston and Homogeneous Two-Phase Flow in the Generator," *Fifth International Conference on MHD Electrical Power Generation*, Vol. 3, Munich, April 19-23, 1971.

113. Goltsova, E. I., and I. T. Aladiev, "Limiting Analysis of Binary Power Stations Using Liquid-Metal MHD Generator," *Twelfth Symposium on the Engineering Aspects of Magnetohydrodynamics*, Argonne, Illinois, March 27-29, 1972.

114. Sychev, V. V., et al., "A Saddle Coil Superconducting Magnet," *Pribory i tekhnika eksperimenta*, No. 2, March-April, 1972.

115. Sychev, V. V., "Problems in Creating Large Superconducting Magnet Systems for MHD Generators," *Symposium on MHD Plants for the Direct Conversion of Thermal Energy to Electrical*, Institute of High Temperatures, Moscow, October 12-16, 1970.